New Trends in Computational Cosmology
(Structure Formation)

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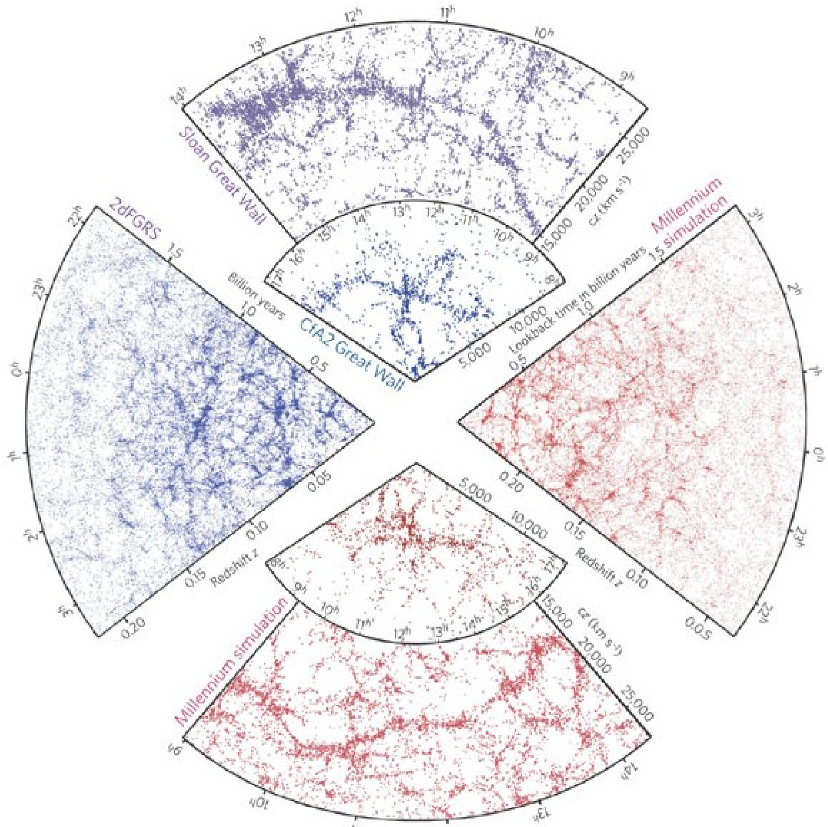
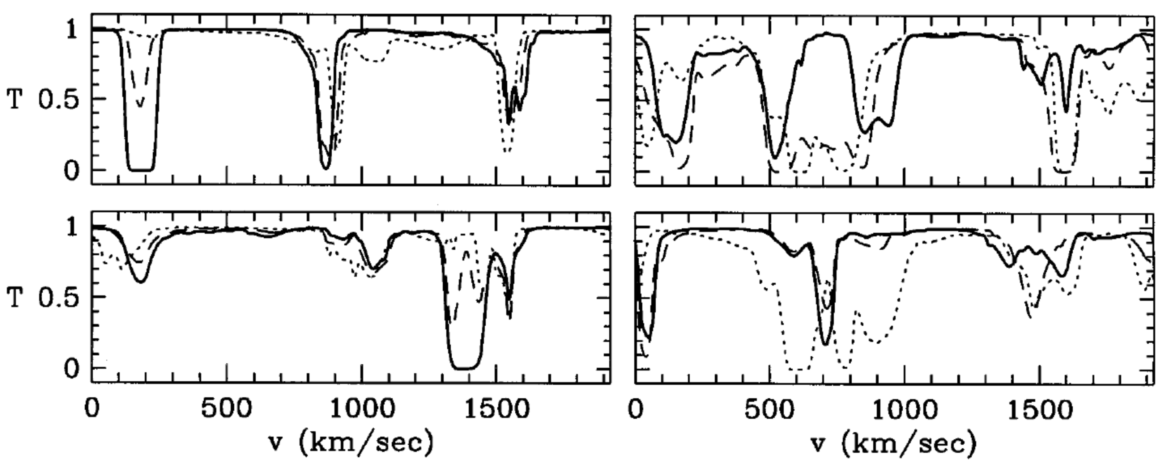
Berkeley, 05/2011

Simulations of Structure Formation



N-body
large scale structure

Springel et al (2005)



hydrodynamics
Lyα forest

Hernquist et al (1996)

Outline

(1) N-body geodesic deviation equation:

dark matter on small scales

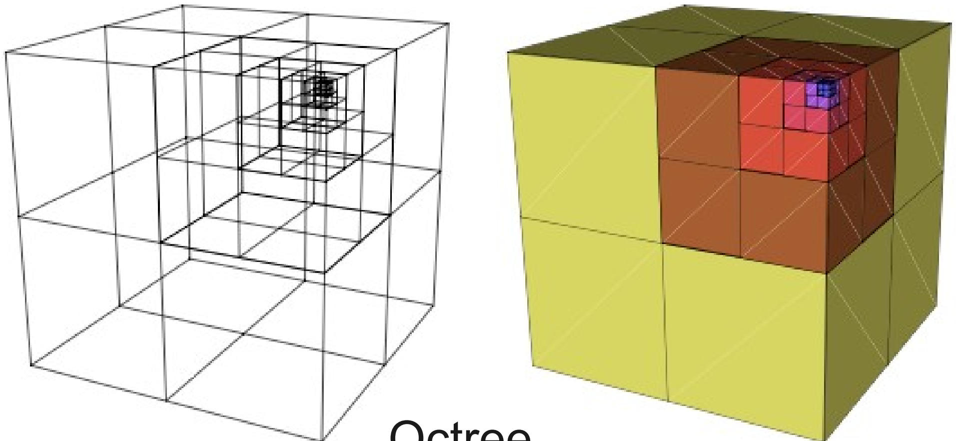
(2) Quasi-Lagrangian finite volume hydrodynamics:

galaxy formation on a moving mesh

N-body geodesic deviation equation

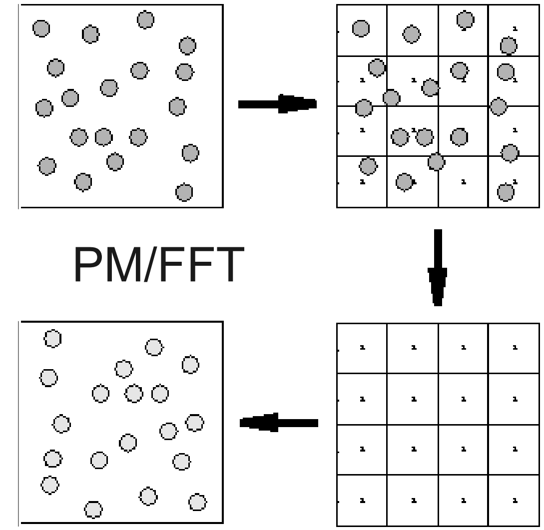
dark matter on small scales

N-body: Numerical Methods

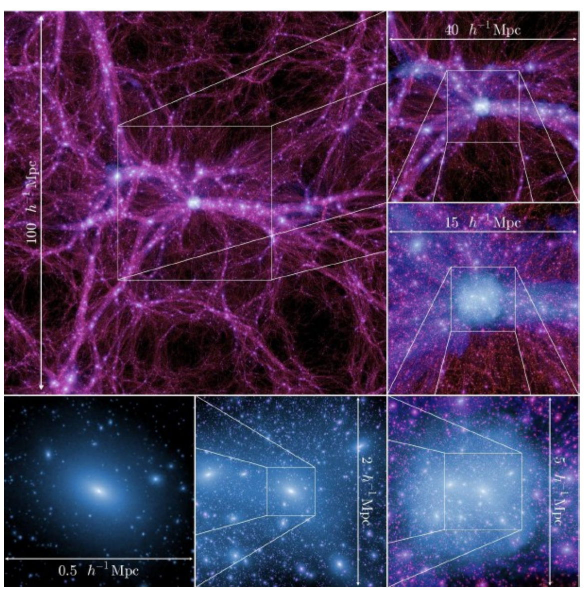


Octree

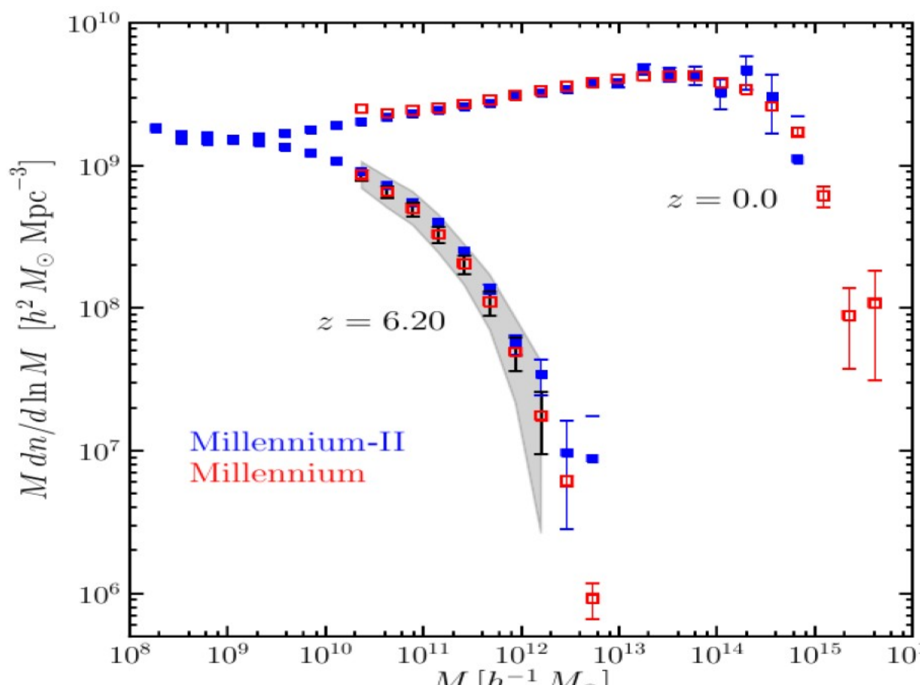
+



= TreePM scheme [short- / long-range force split]



Boylan-Kolchin et al (2009)



N-body: State-of-the-Art

Angulo et al (submitted)

303 billion particles

L = 3 Gpc/h

~700 million halos
at z=0

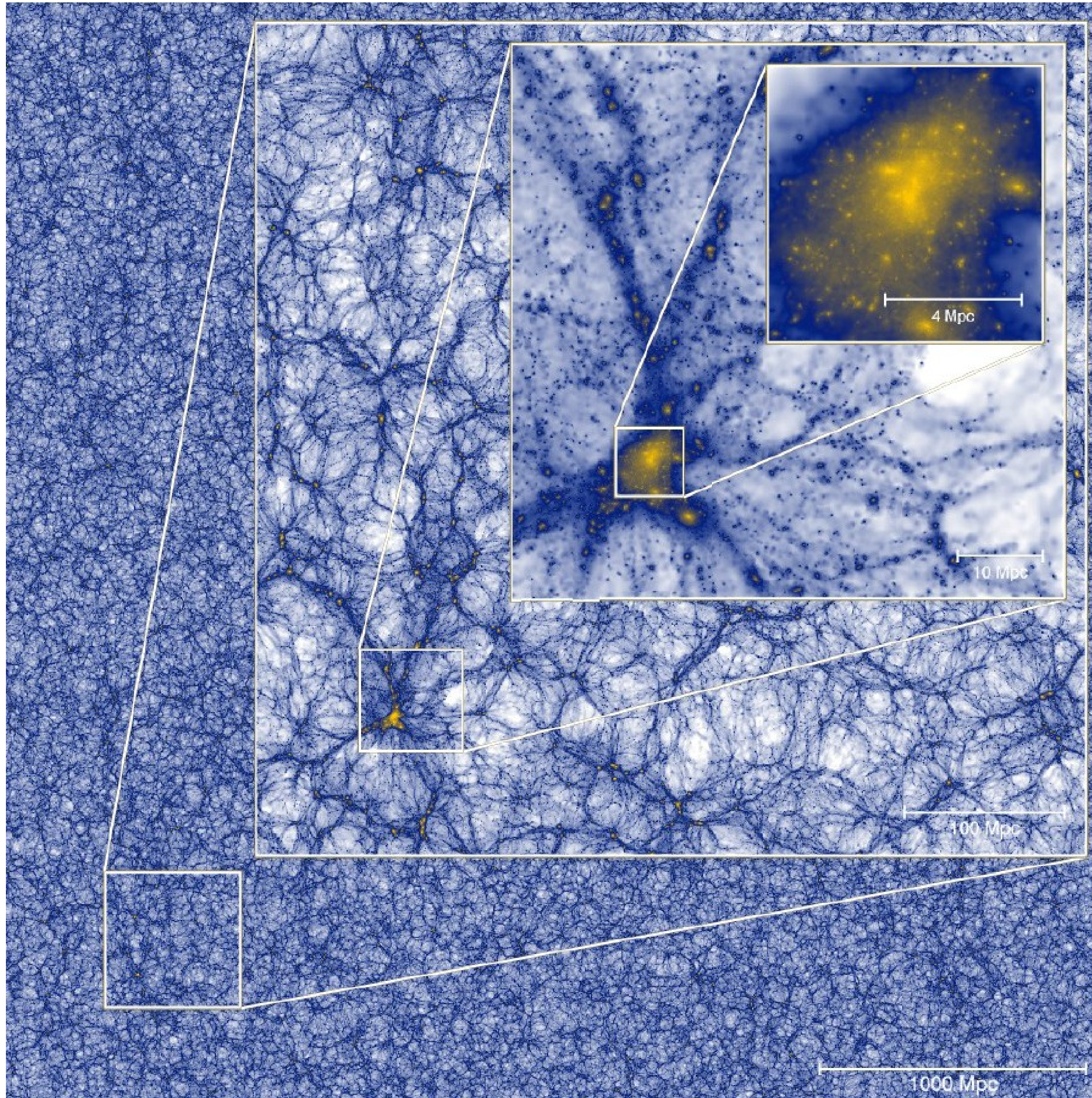
~25 billion (sub)halos
in mergers trees

$m_p = 6.1 \times 10^9\ M_\odot/h$

12288 cores,
30 TB RAM on
Supercomputer
JuRoPa in Juelich

2.7 million CPU-hours

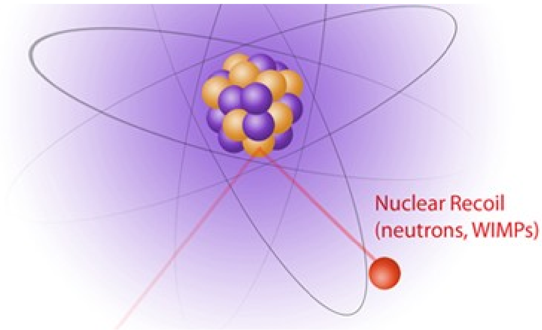
[Springel]



The Hunt for Dark Matter

Direct searches:
nuclear recoil events

CRESST, XENON, ZEPLIN,
EDELWEISS, CDMS, DAMA, ...

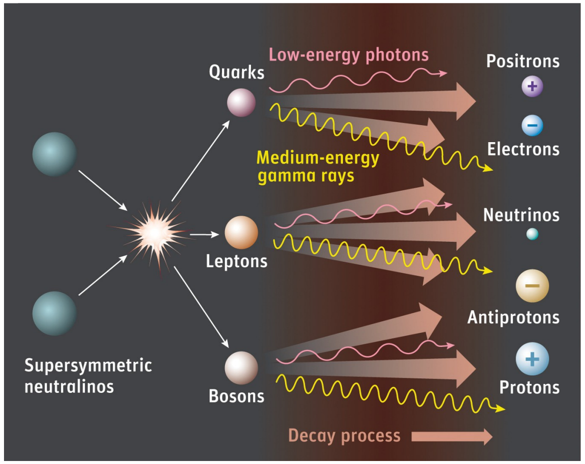


Accelerator searches:
producing DM

LHC

Indirect searches:
annihilation products

FERMI, PAMELA, ...



<u>Usually assumed astrophysical input:</u>

Density: ~0.3 GeV / c^2 / cm^3

Velocity: Maxwellian

Standard Halo Model (SHM):

- **Smooth mass distribution**
- **Smooth velocity distribution**
- **'Featureless' phase-space**

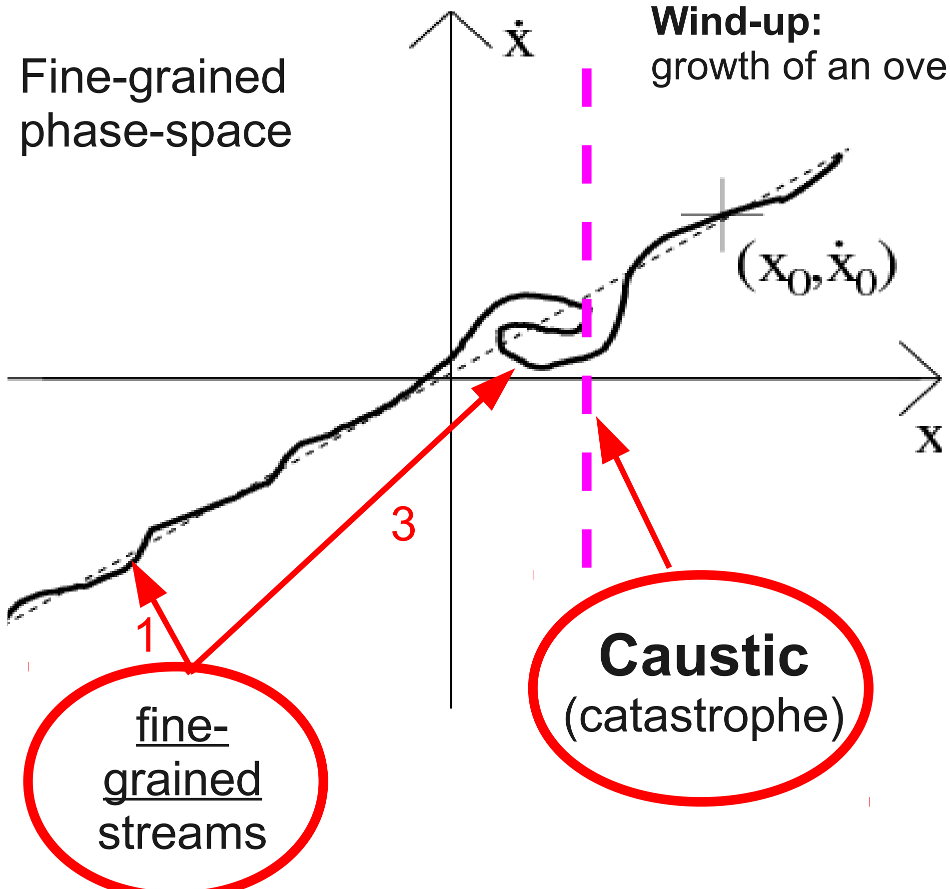
CDM – Small Scales

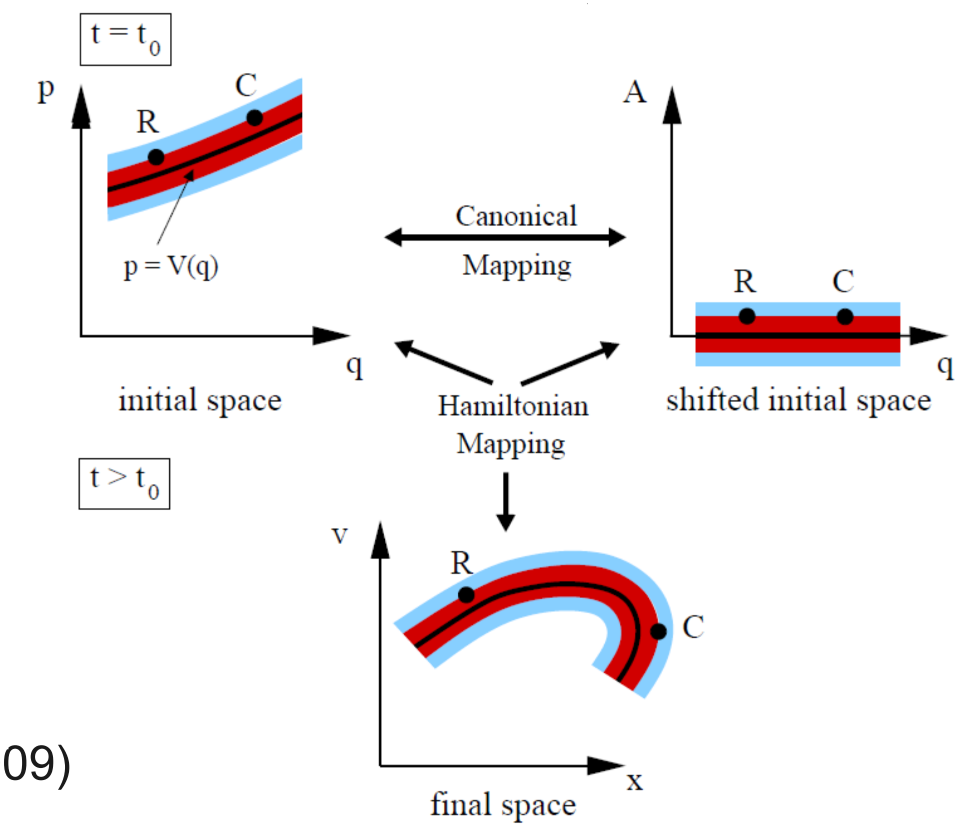
CDM is **cold** and **collisionless** → **CDM restricted to 3D hypersurface in 6D phase-space**

Thickness of line:
primordial velocity dispersion
Amplitude of wiggles:
velocity due to density perturbations
Wind-up:
growth of an overdensity

symplectic
mapping

Fine-grained
phase-space





White & MV (2009)

Analytic Predictions

Self-similar halo formation:

Fillmore & Goldreich (1984), Bertschinger (1985),
Mohayaee & Salati (2008);
Mohayaee et al (2006); ...

Caustic ring model:

Duffy & Sikivie (2008);
Natarajan & Sikivie (2008);
Onemli & Sikivie (2007);
Natarajan & Sikivie (2007);
Sikivie et al (1997); ...

General arguments:

Hogan (2001)

Predictions

- ~100 streams at solar position
- significant annihilation boost
- strong caustic rings
- discrete velocity distribution
- distinct caustic structures

→ significant effects on search experiments

How realistic are these models?

Caustic densities? Number of streams? Boost factor?

Resolving Fine-Grained Structure with N-body Simulations

Problem: N-body simulations have too coarse phase-space sampling
(→ missing many orders of magnitude in mass resolution/particle number)

Solution: Follow the local phase-space evolution for each particle
(→ with a phase-space geodesic deviation equation)

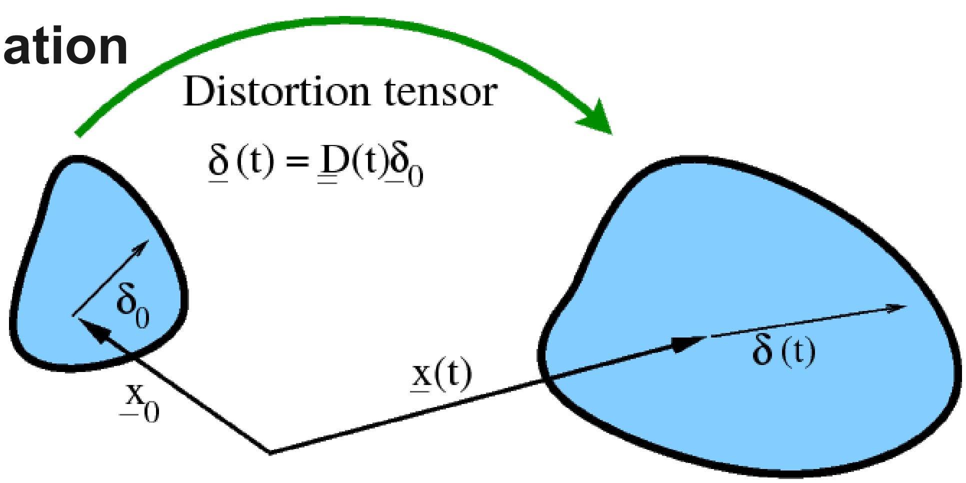
- **calculation of stream density**

- **identification of caustics**

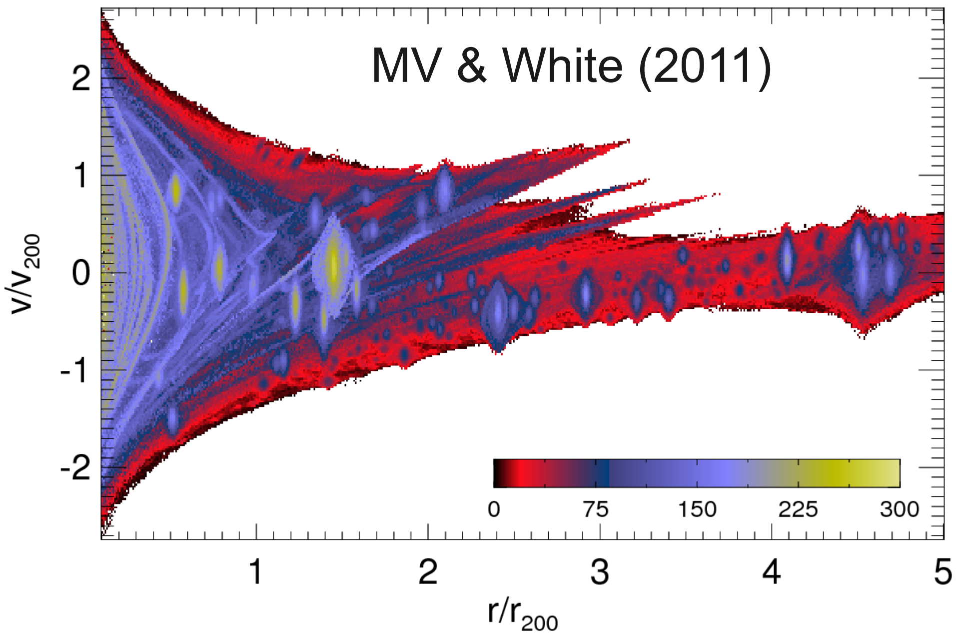
- **Monte-Carlo estimate for intra-stream annihilation**

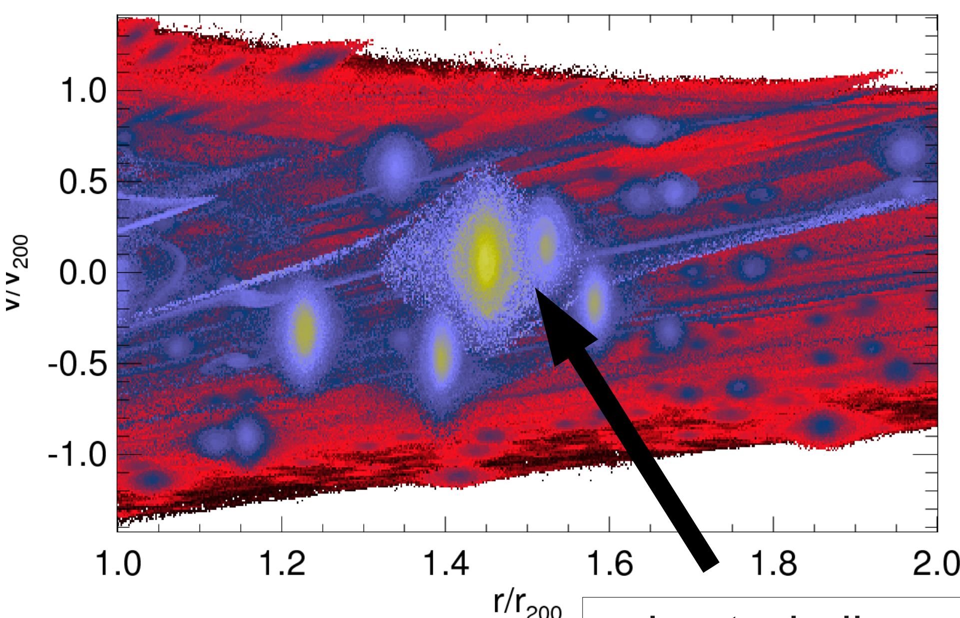
→ allows caustic annihilation calculation

MV et al (2008)

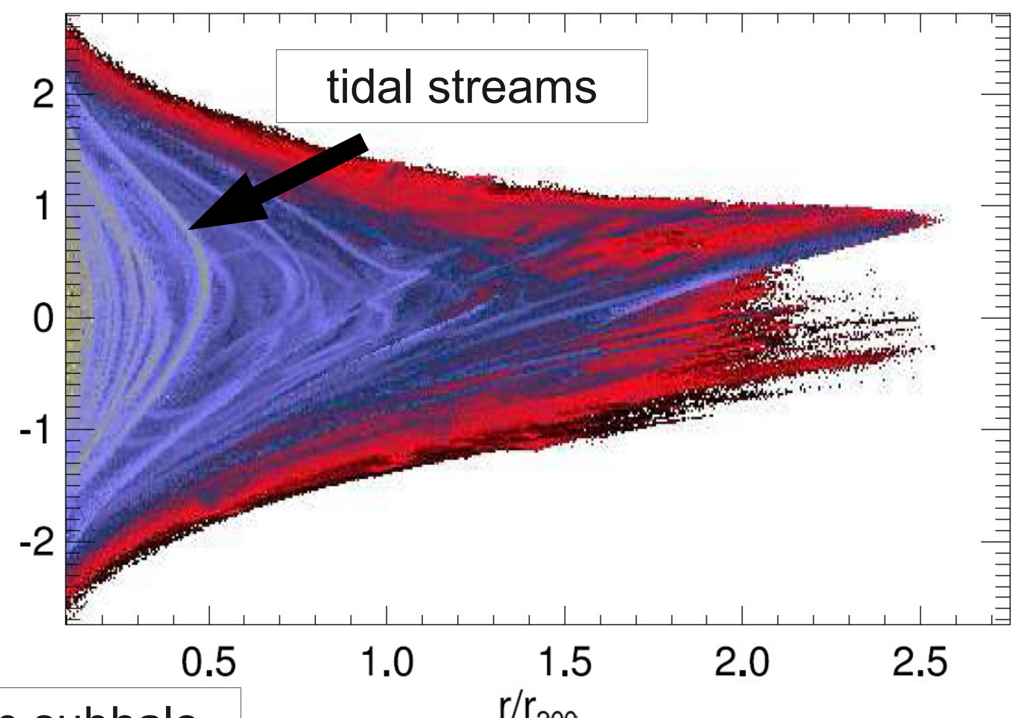


Fine-grained Structure of Milky Way like Halos

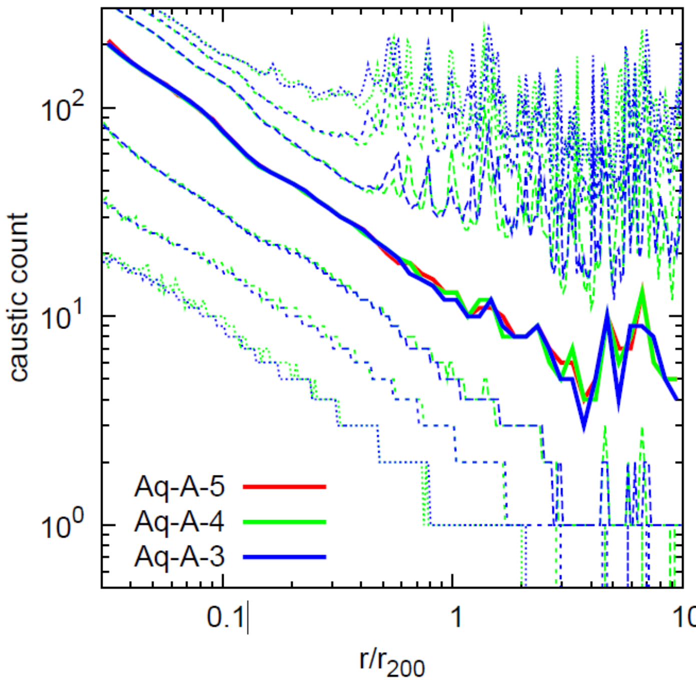




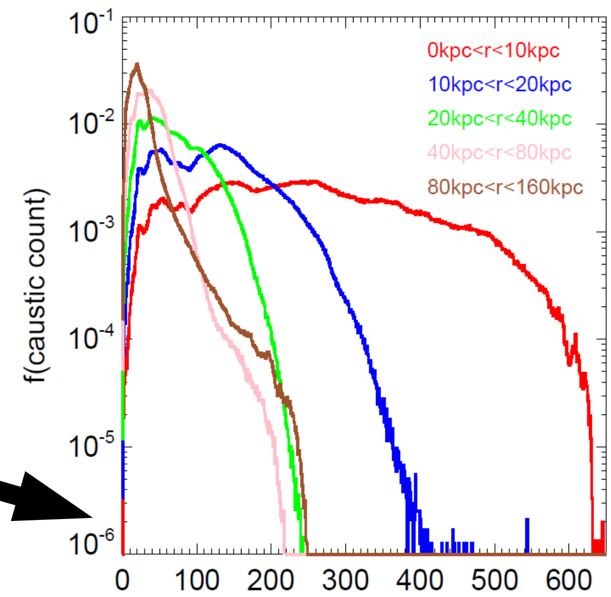
sheet winding up in subhalo



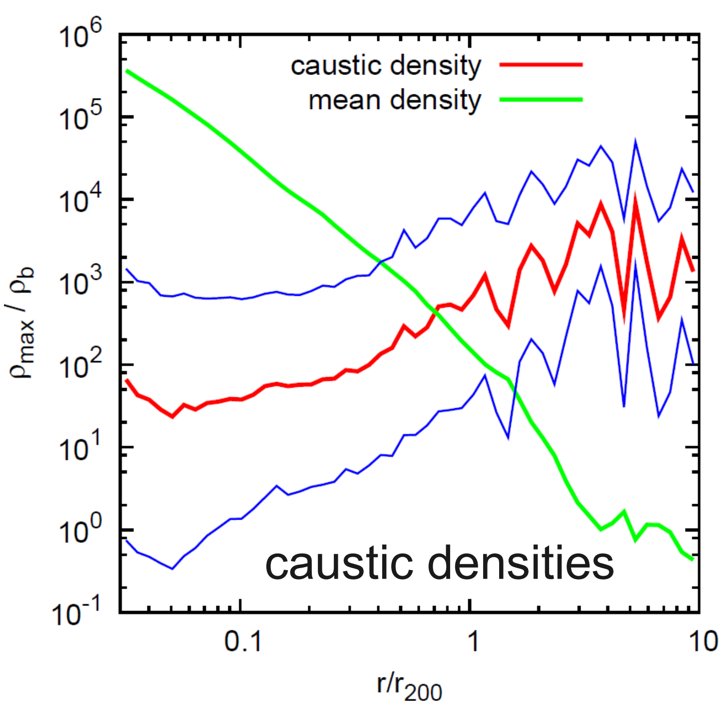
Fine-grained Caustics



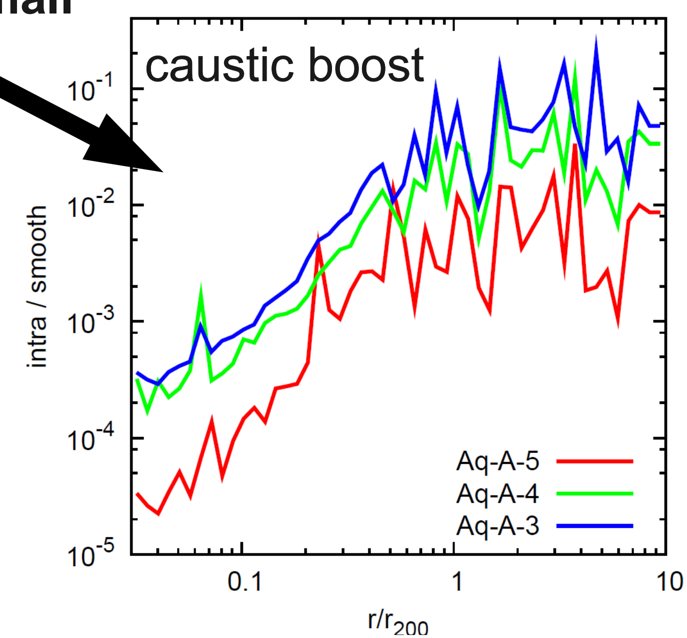
caustic count profiles **converged**



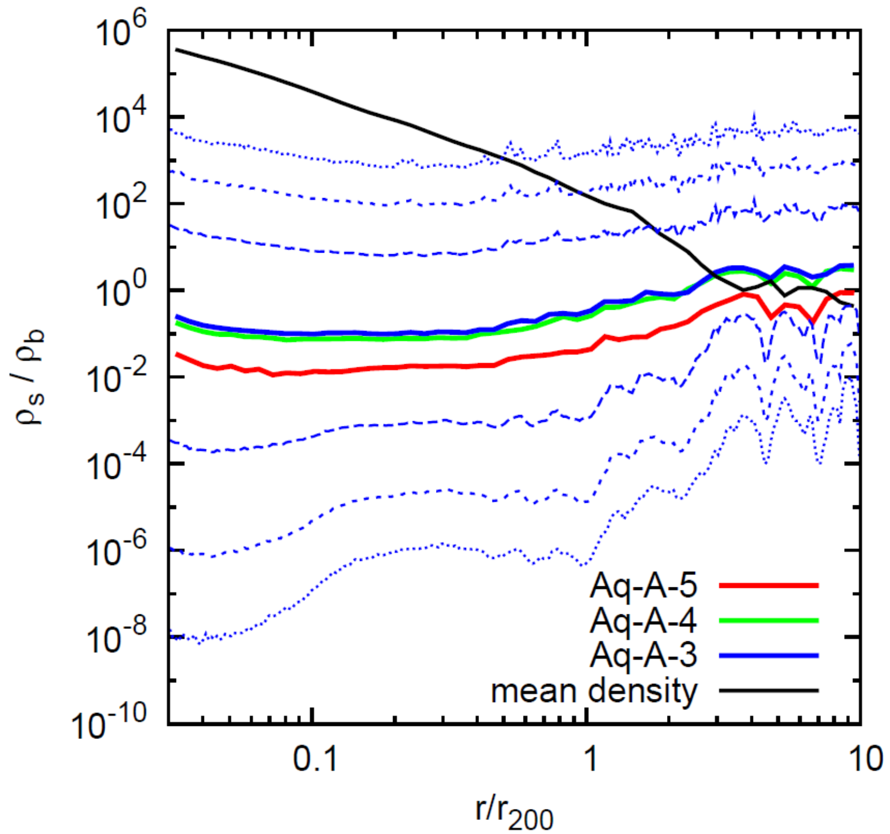
caustic count tracks **dynamical age**



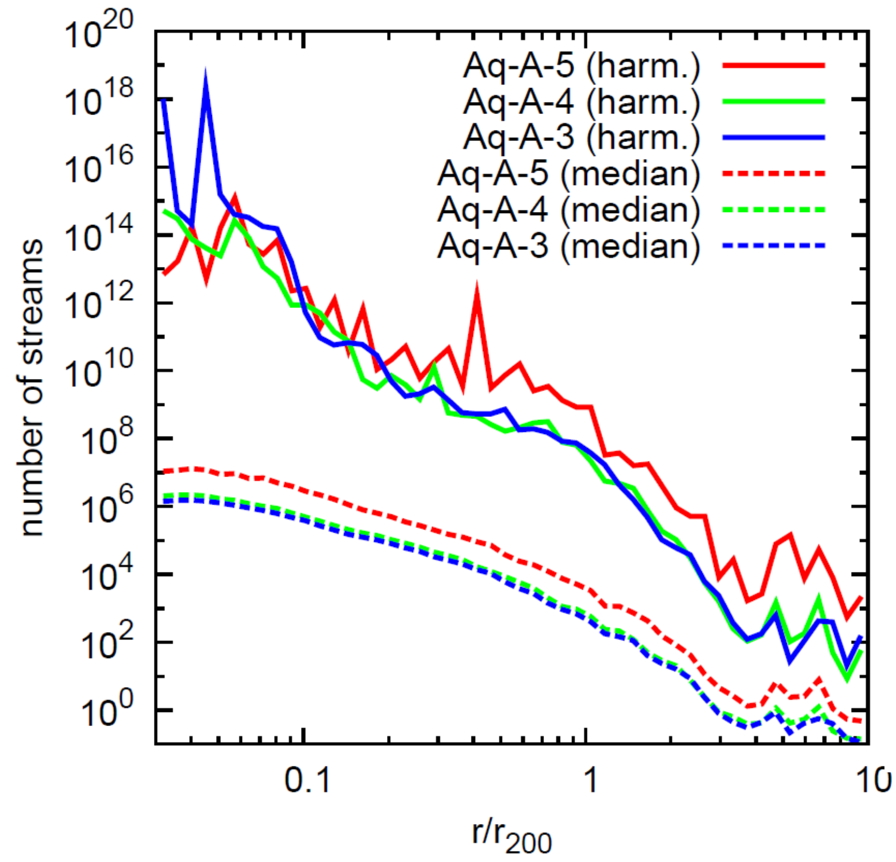
caustic **boost very small**



Fine-grained streams

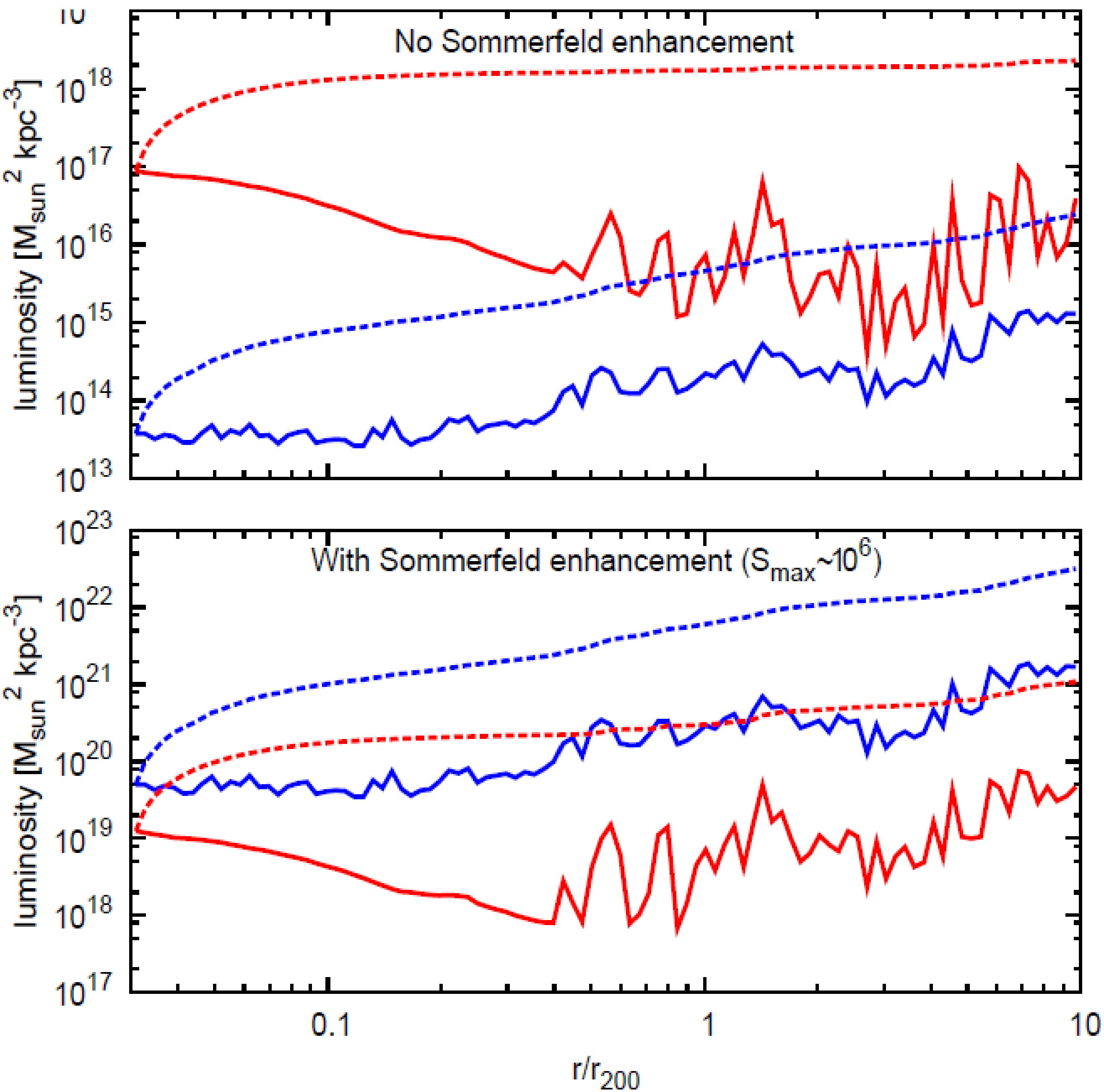


stream densities **converged**



huge number of streams in inner halo

Sommerfeld Enhancement



regions of low velocity dispersion dominate annihilation signal:

→ streams contribute a lot

→ caustics negligible in such a scenario

red: smooth halo
blue: streams

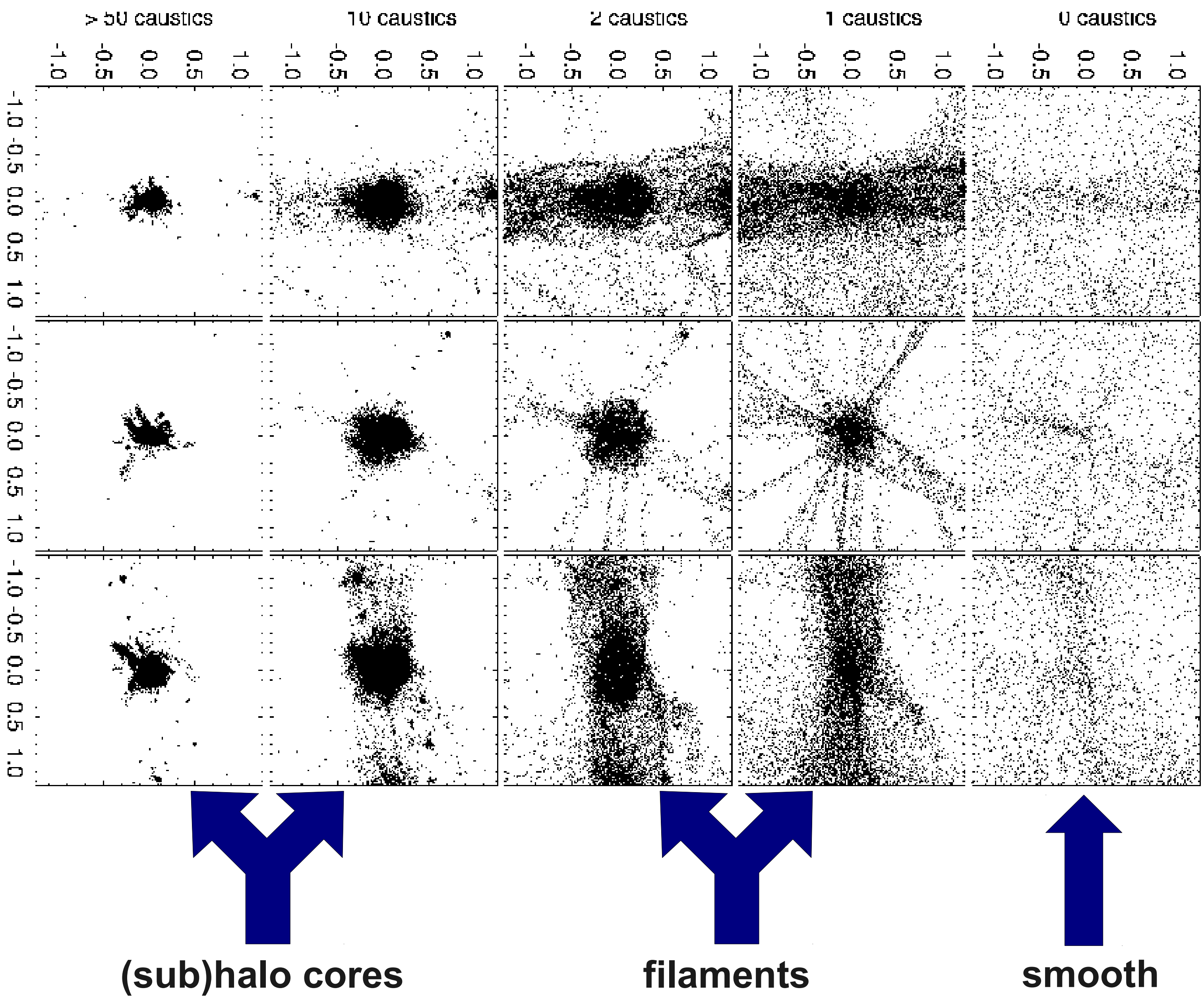
Zavala, MV, Slatyer, Loeb, Springel (2011)

Implications

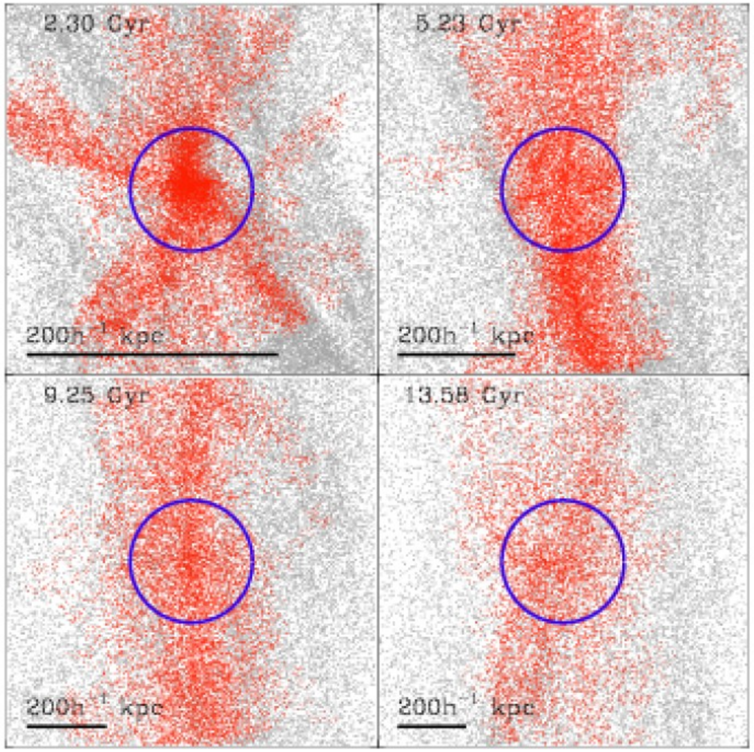
- no massive streams near the Sun
- no discrete velocity distribution
- >>100 streams near the Sun
- no dense caustic structures
- N-body simulations do not miss much caustic annihilation

Local DM phase-space distribution is very smooth!

Further Applications:
Filtering the Cosmic Web



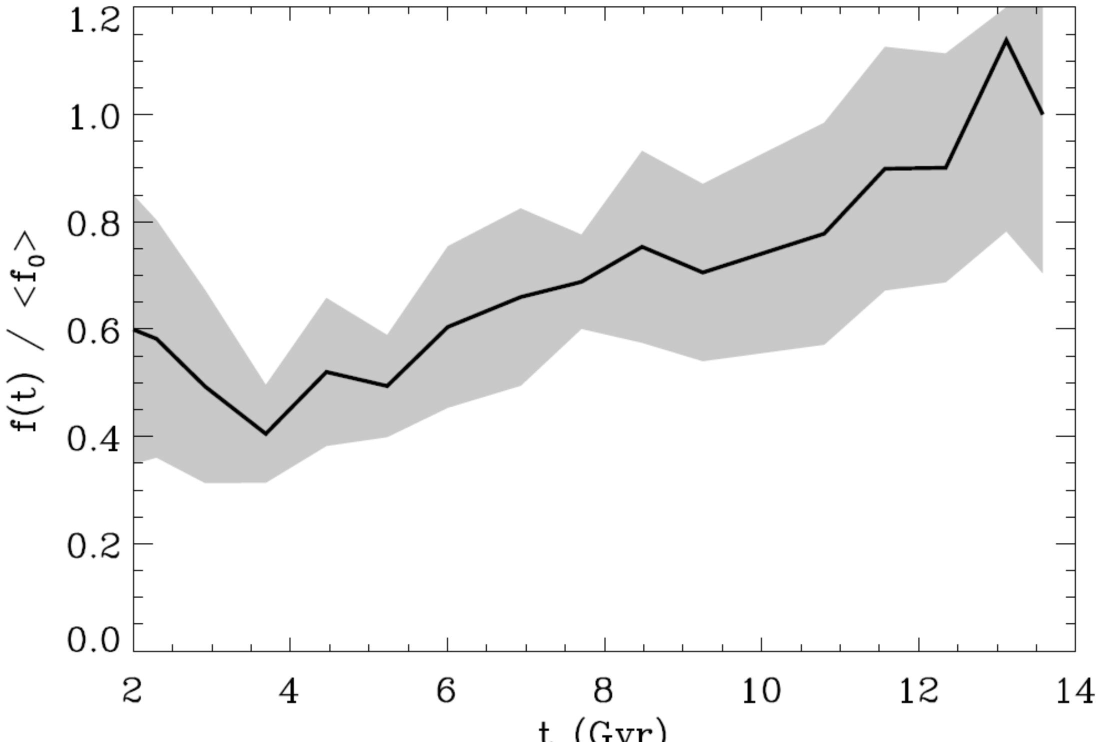
Filaments around Halos



filament size relative to virial
radius increase with time
→ later infall from filaments with
larger cross-section

FoF on low caustic
count particles

Vera-Ciro et al (2011)

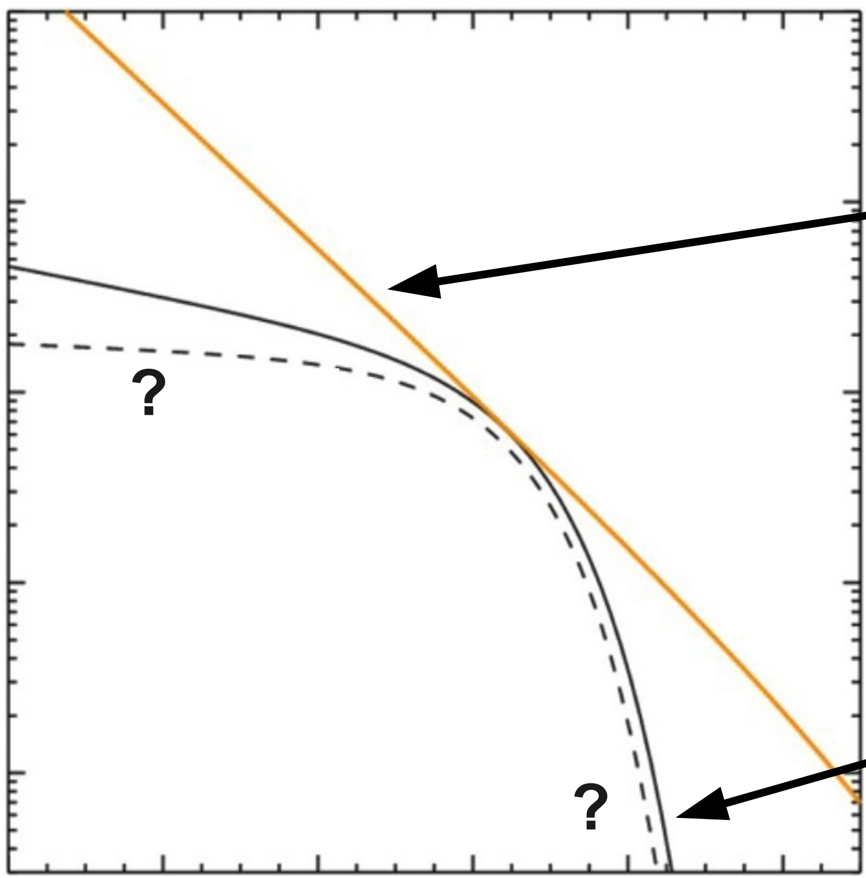


Quasi-Lagrangian finite volume hydrodynamics

galaxy formation on a moving mesh

Galaxy Formation Problem: Dark Matter ↔ Baryons

modeling baryon physics is more complicated/uncertain



DM halo mass function

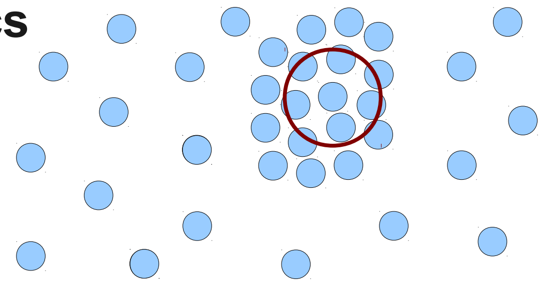
?

galaxy luminosity function

Hydrodynamics: Numerical Methods

Smoothed-Particle-Hydrodynamics
(e.g. GADGET)

widely used in cosmological applications because of Lagrangian character

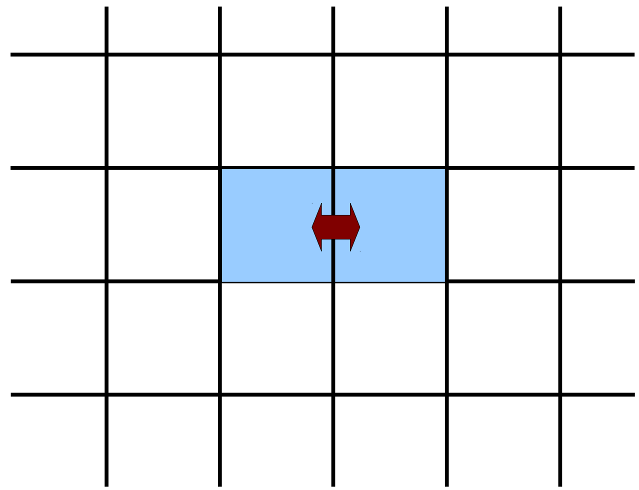


$$F_s(\mathbf{r}) = \int F(\mathbf{r}) W(\mathbf{r}-\mathbf{r}', h)\,\mathrm{d}\mathbf{r}'$$

$$F_s(\mathbf{r}) \simeq \sum_j \frac{m_j}{\rho_j} F_j W(\mathbf{r}-\mathbf{r}_j, h)$$

Finite-Volume-Methods
(e.g. ENZO)

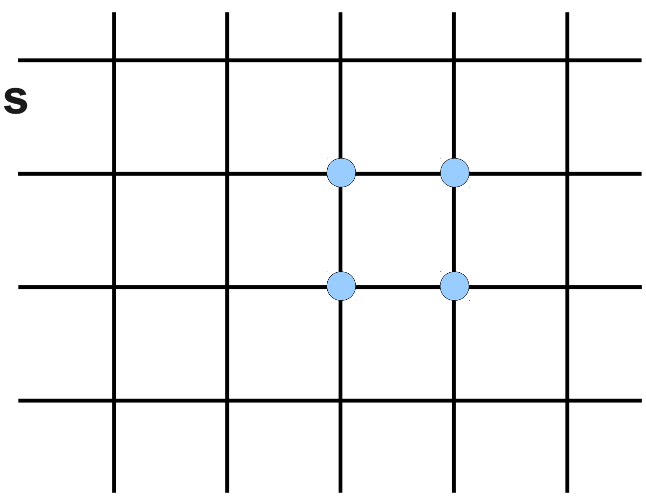
typically Eulerian approach implemented as AMR



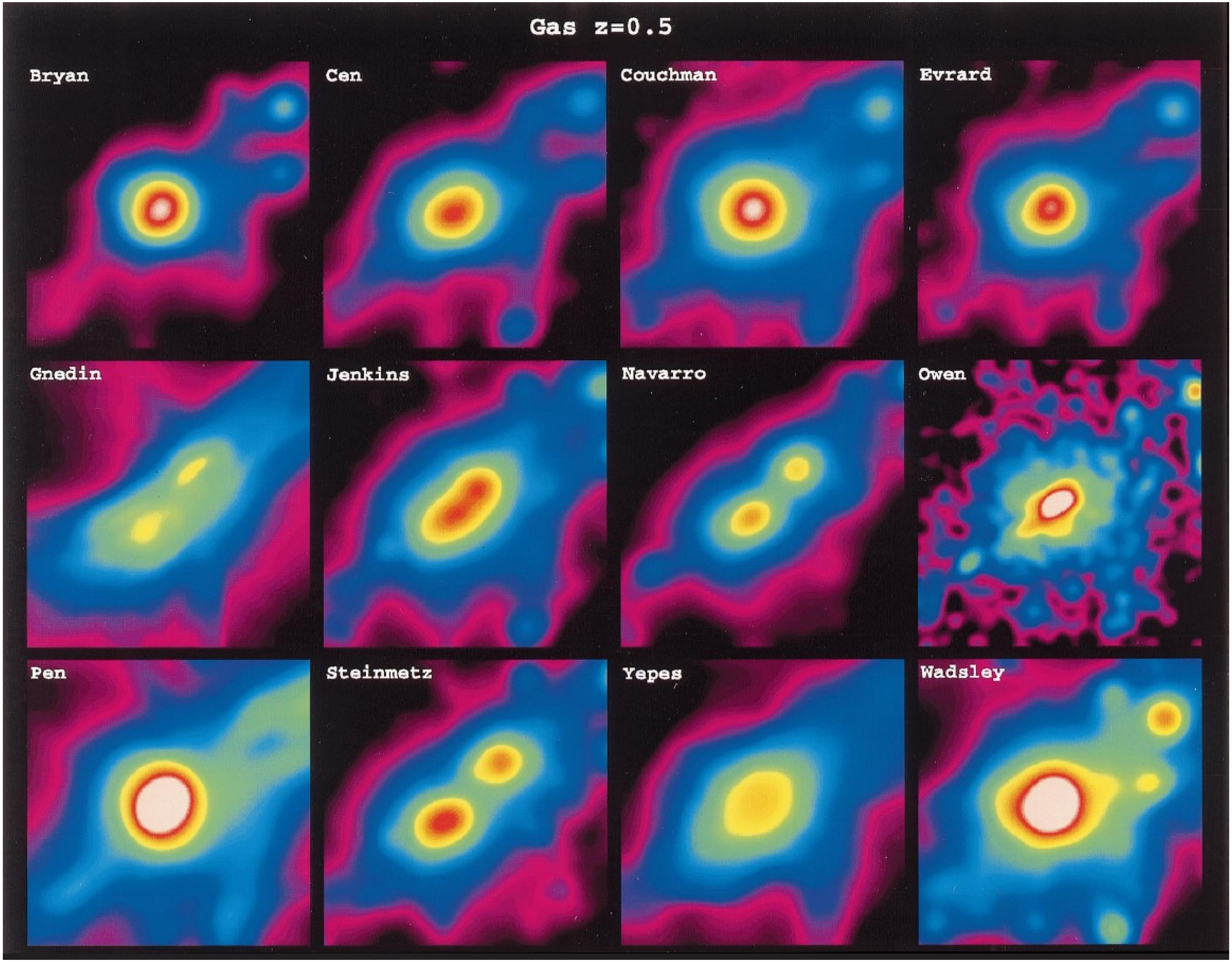
$$\boldsymbol{Q}_i = \begin{pmatrix} m_i \\ \boldsymbol{p}_i \\ E_i \end{pmatrix} = \int_{V_i} \boldsymbol{U}\,\mathrm{d}V$$

$$\frac{\mathrm{d}\boldsymbol{Q}_i}{\mathrm{d}t} = -\sum_j A_{ij} \boldsymbol{F}_{ij}$$

Finite-Differencing-Methods



Uncertainties



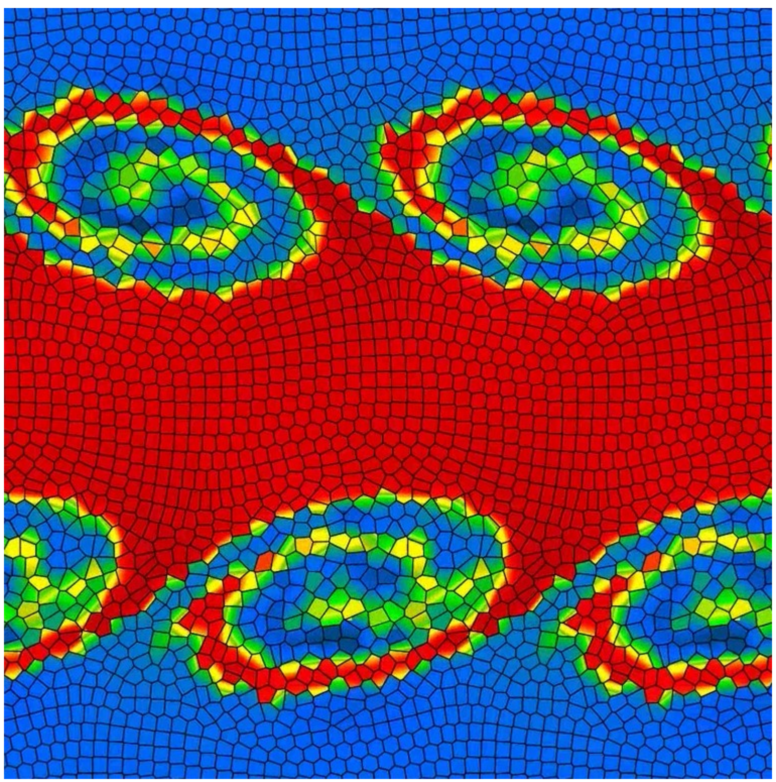
Frenk et al (1999)

Moving Mesh Hydrodynamics

Lagrangian Methods
(SPH)
e.g.: Gadget

Eulerian Methods
(AMR)
e.g.: Enzo

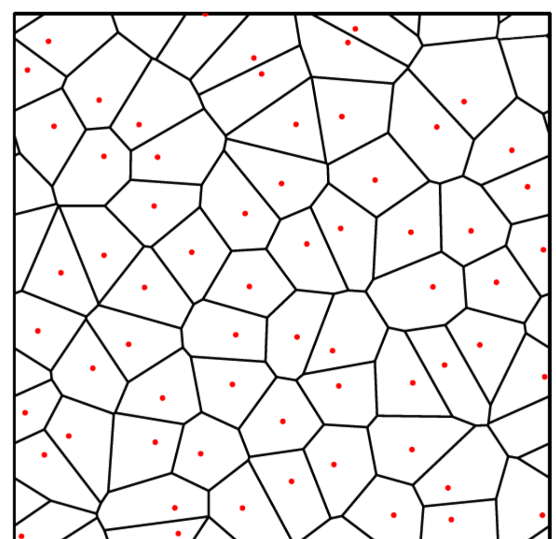
Quasi-Lagrangian Hybrid Scheme: AREPO (Springel, 2010)
TESS (Duffell & MacFadyen, 2011)



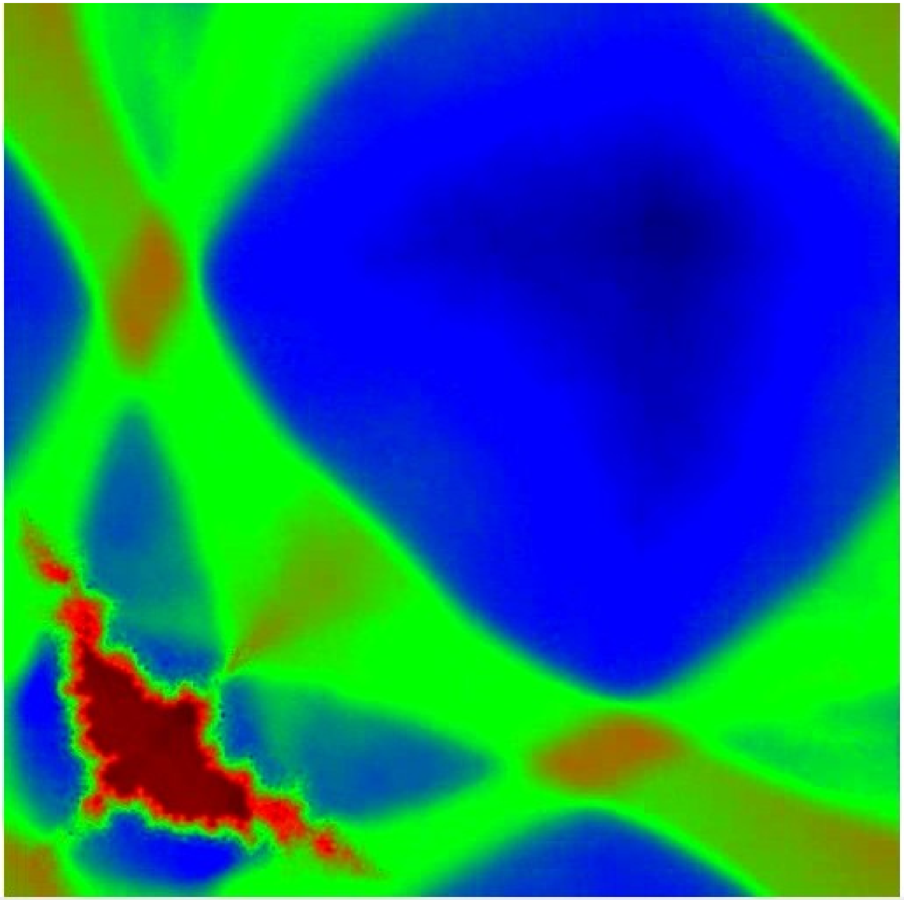
Moving Voronoi Mesh

tests demonstrated that AREPO seems to work very well compared to other hydro schemes

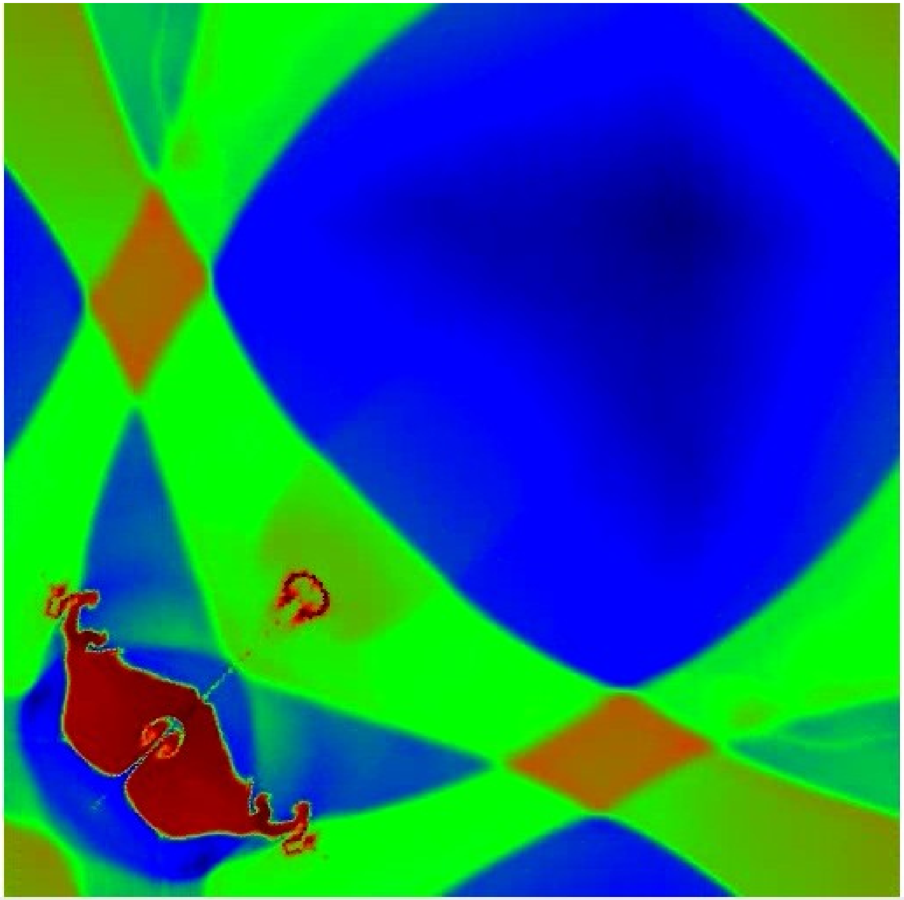
How does it perform on 'real' problems?



Test Problem I



SPH

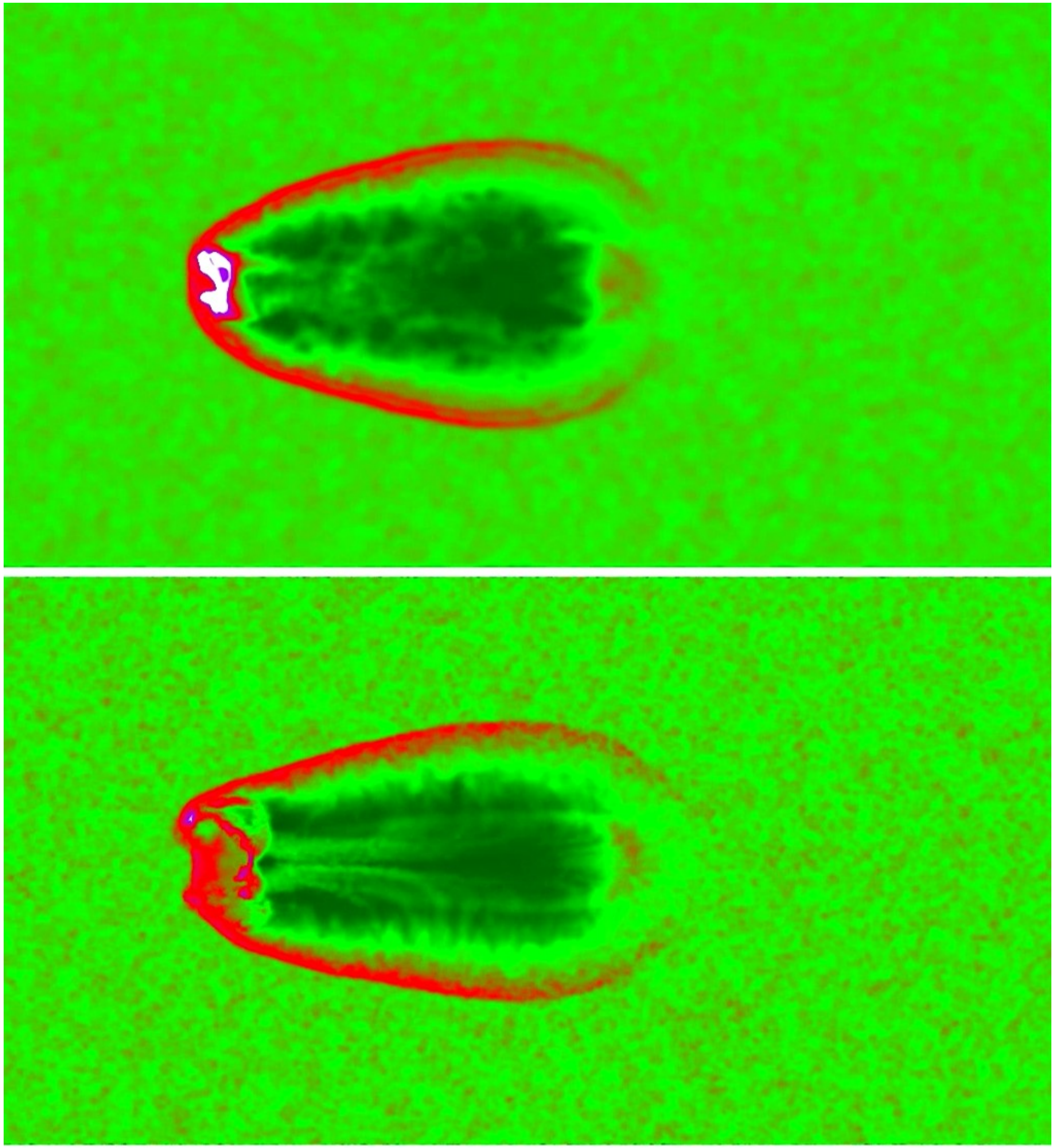


MOVING MESH

2D shocktube → interacting shocks

Sijacki et al (in prep)

Test Problem II



SPH

Blob test

MOVING MESH

Sijacki et al (in prep)

Cosmological Simulations

How does AREPO perform for cosmological problems?

What are the differences to previous SPH runs?

What are the implications for the modeling of sub-resolution physics?

Test code and compare to SPH:

• sub-resolution physics is *identical*

• gravity solver is *identical*

Direct comparison possible

Only difference: hydro solver: **MOVING MESH vs. SPH**

What differences are caused by new hydro scheme?

Simulation Setup

Cosmology:

- Ω_M=0.27, Ω_L=0.73, Ω_B=0.045
- σ_8=0.8, H_0=70 km/s/Mpc

Implemented Physics:

- Radiative Cooling: primordial mixture of H and He
- UV Background (updated Haardt&Madau)
- Star Formation/Feedback: Springel&Hernquist (2003)

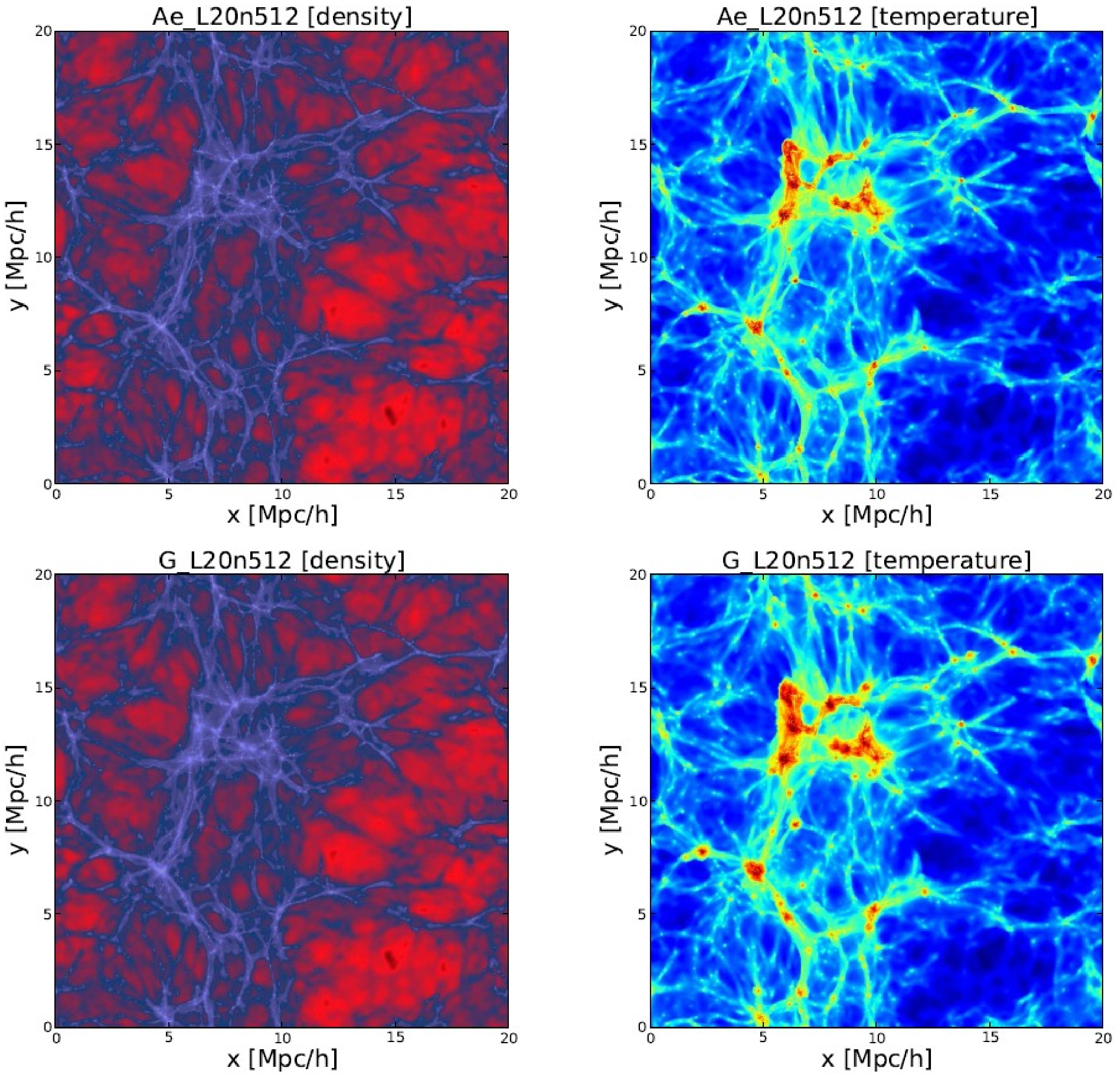
AREPO:

- de-/refinement
- mesh regularization

MV et al (in prep)
Keres et al (in prep)
Sijacki et al (in prep)

Name	Code (mode)	Boxsize$[(\mathrm{Mpc}/h)^3]$	hydro elements	DM particles	$m_{\mathrm{DM}}[\mathrm{M}_\odot/h]$	$m_{\mathrm{target/SPH}}[\mathrm{M}_\odot/h]$
Ad_L20n512	AREPO (dual entropy)	20^3	512^3	512^3	7.444×10^5	3.722×10^6
Ae_L20n512	AREPO (energy)	20^3	512^3	512^3	7.444×10^5	3.722×10^6
G_L20n512	GADGET	20^3	512^3	512^3	7.444×10^5	3.722×10^6
Ad_L20n256	AREPO (dual entropy)	20^3	256^3	256^3	5.955×10^6	2.977×10^7
Ae_L20n256	AREPO (energy)	20^3	256^3	256^3	5.955×10^6	2.977×10^7
G_L20n256	GADGET	20^3	256^3	256^3	5.955×10^6	2.977×10^7
Ad_L20n128	AREPO (dual entropy)	20^3	128^3	128^3	4.764×10^7	2.382×10^8
Ae_L20n128	AREPO (energy)	20^3	128^3	128^3	4.764×10^7	2.382×10^8
G_L20n128	GADGET	20^3	128^3	128^3	4.764×10^7	2.382×10^8

Global Density and Temperature Structure

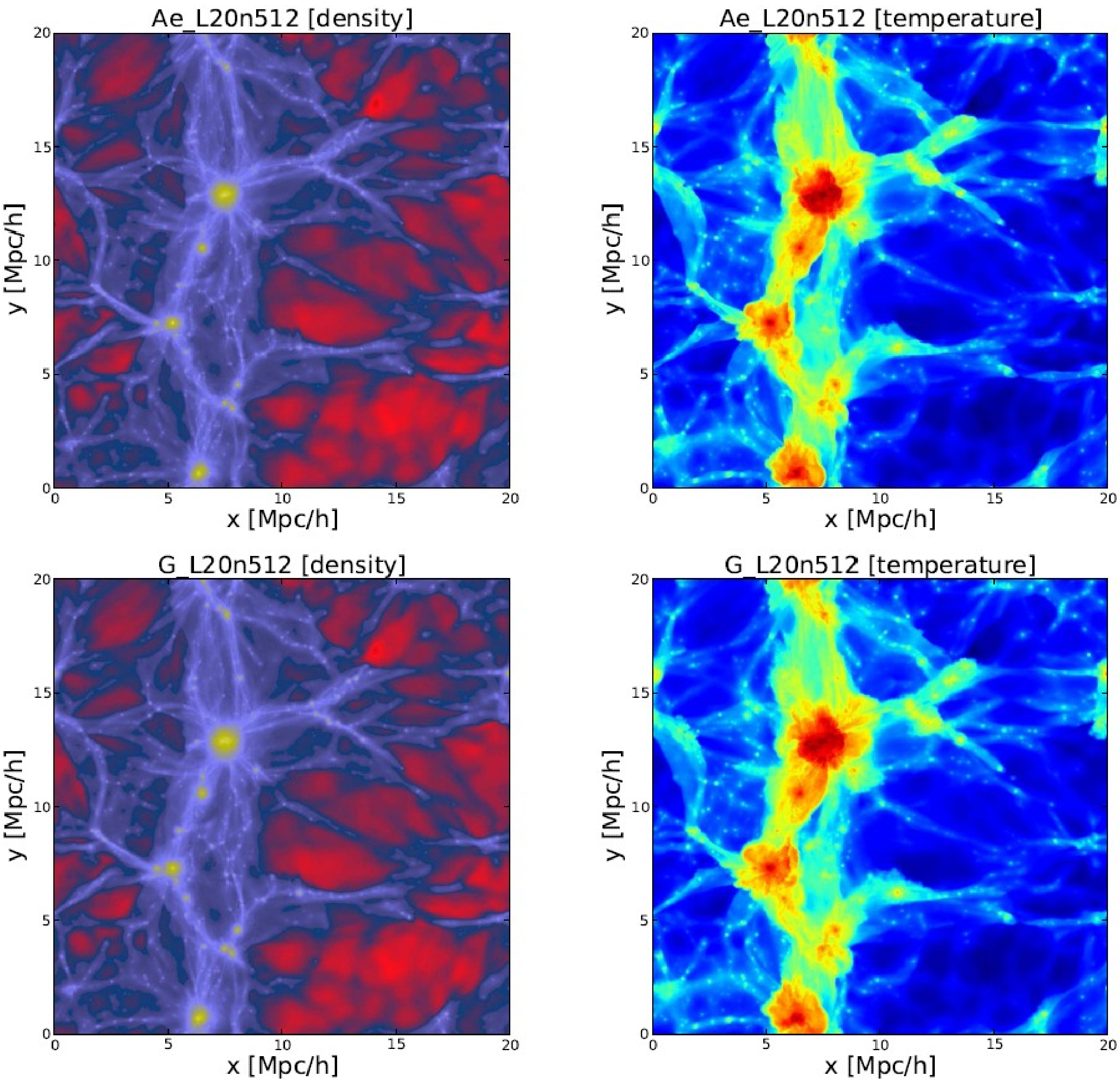


MOVING MESH

z=2

SPH

Global Density and Temperature Structure

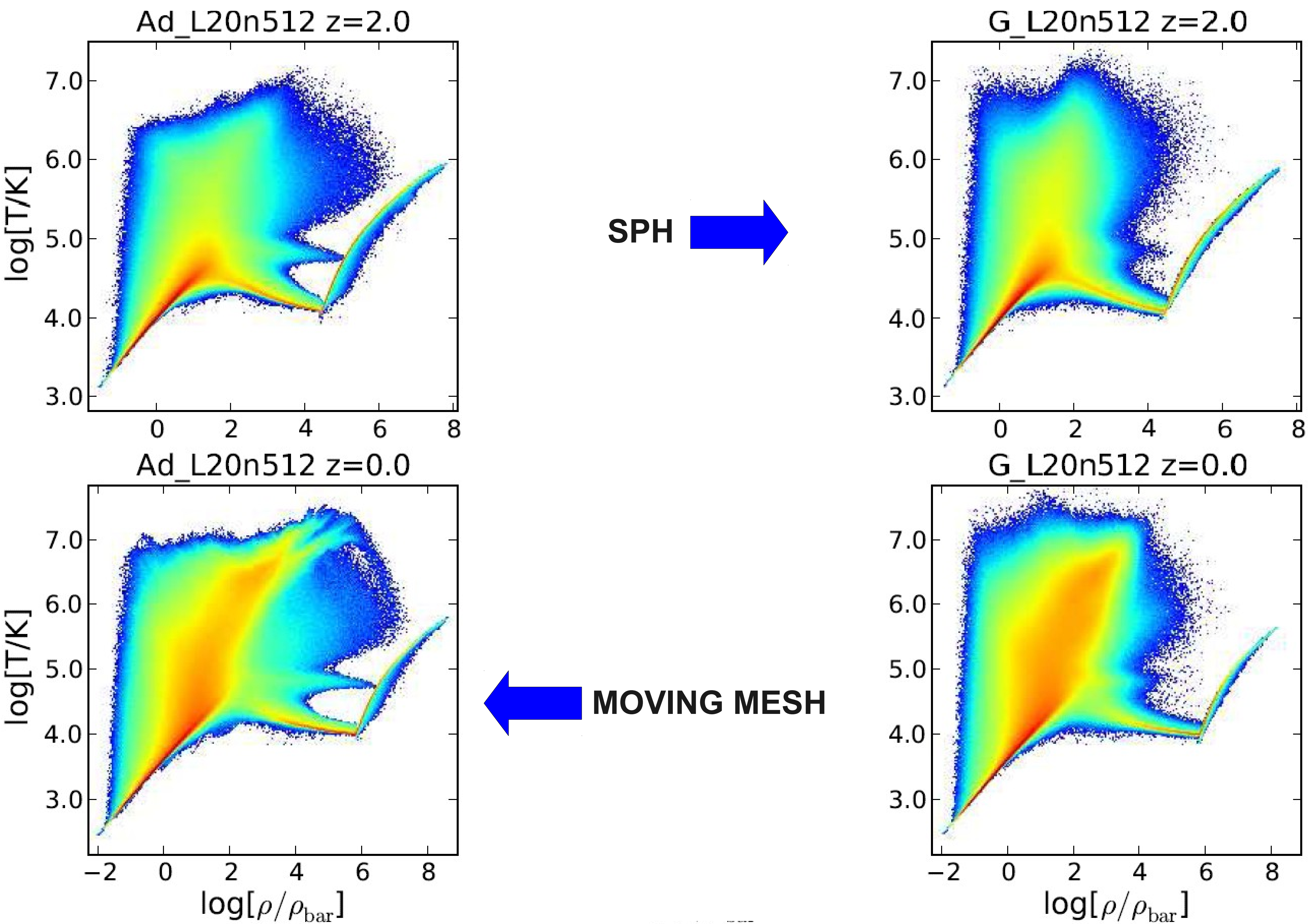


MOVING MESH

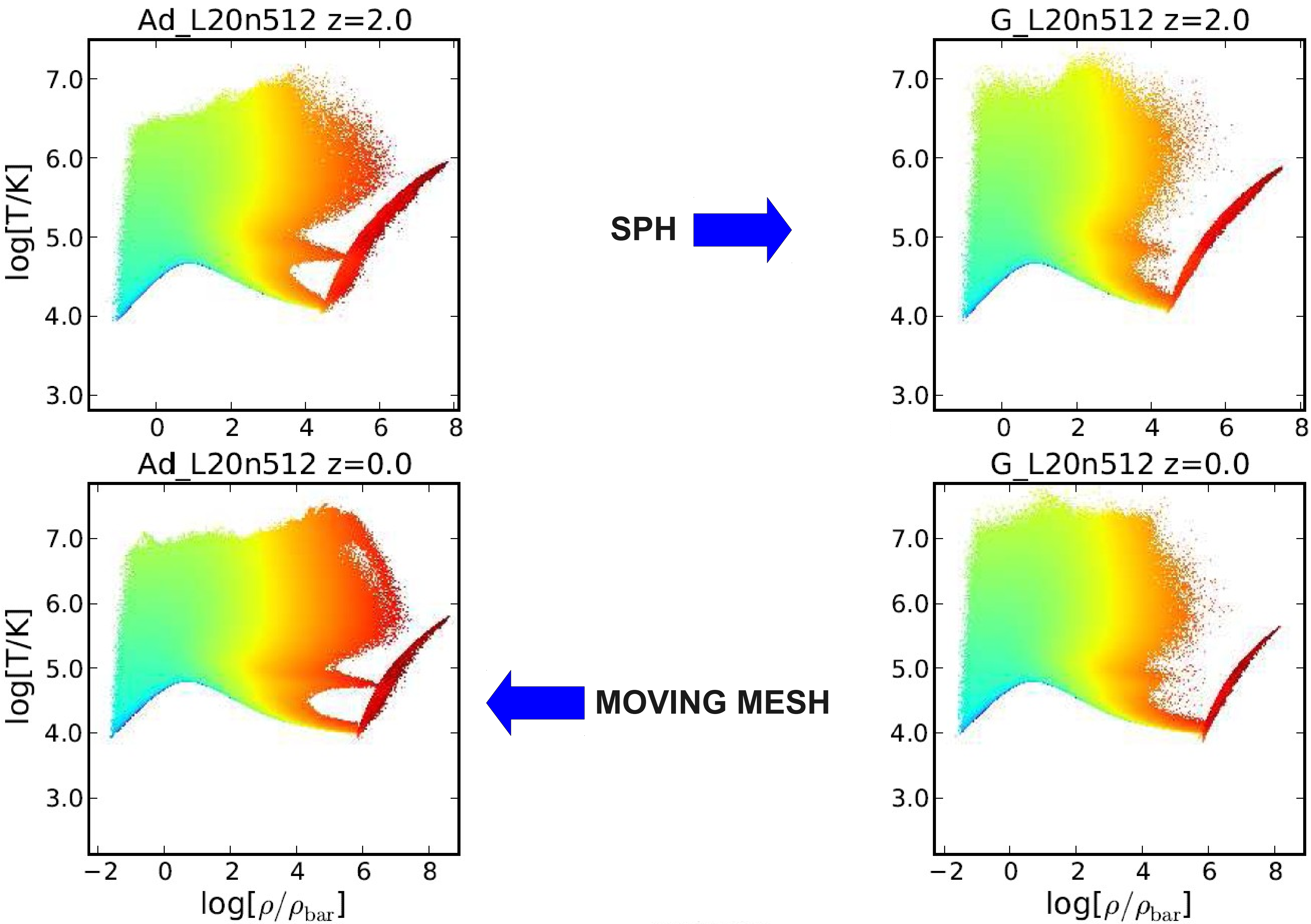
z=0

SPH

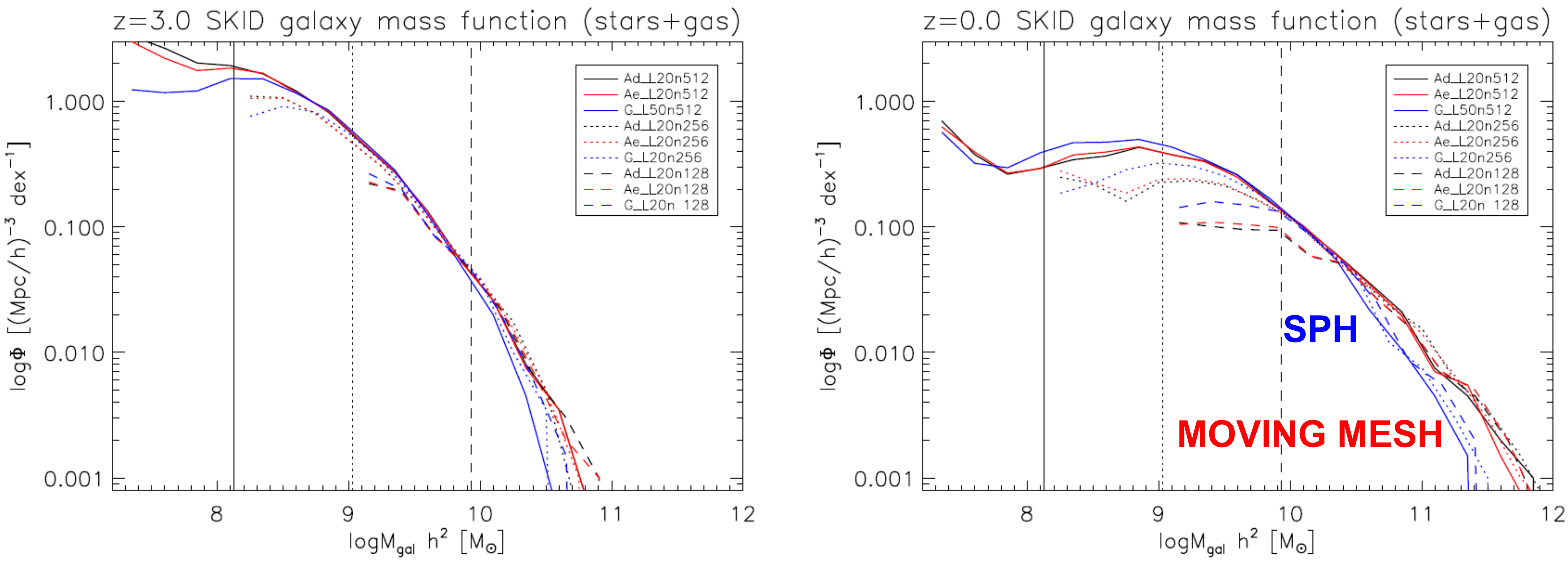
Gas Phase Diagram



Cooling Rates

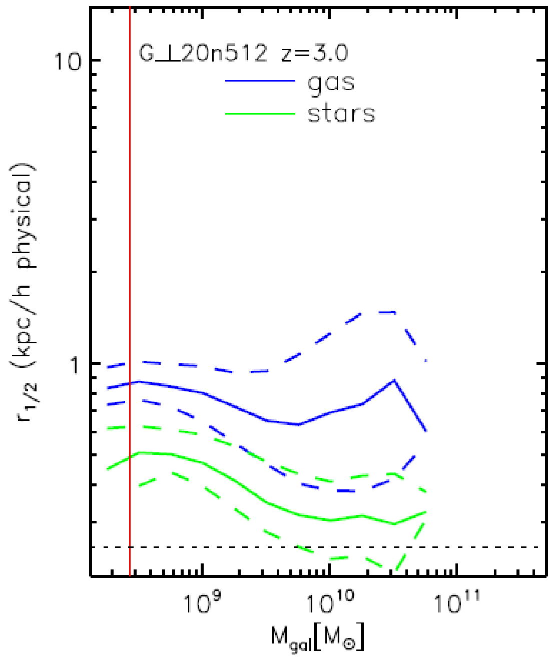


Galaxy Mass Function

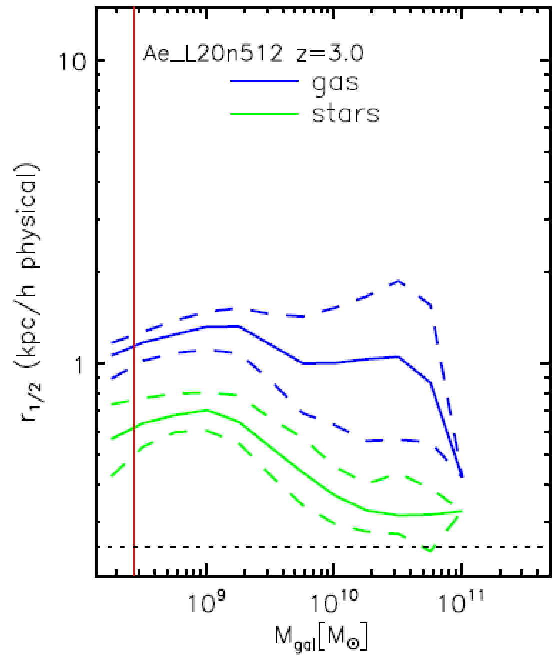


more massive galaxies in AREPO

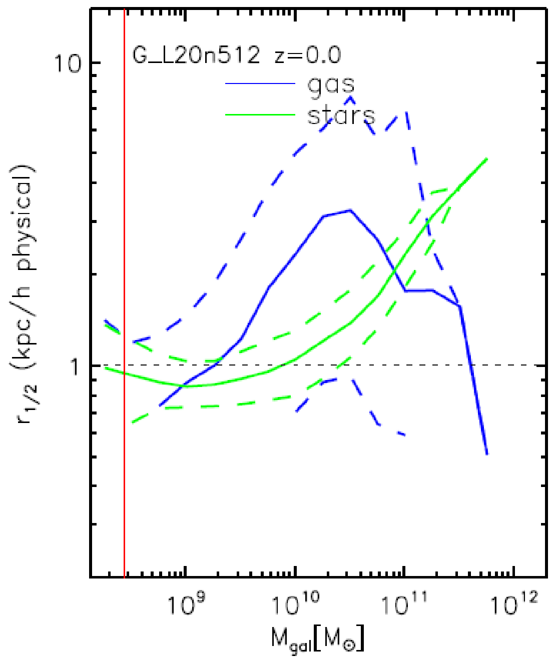
Galaxy Sizes



MOVING MESH

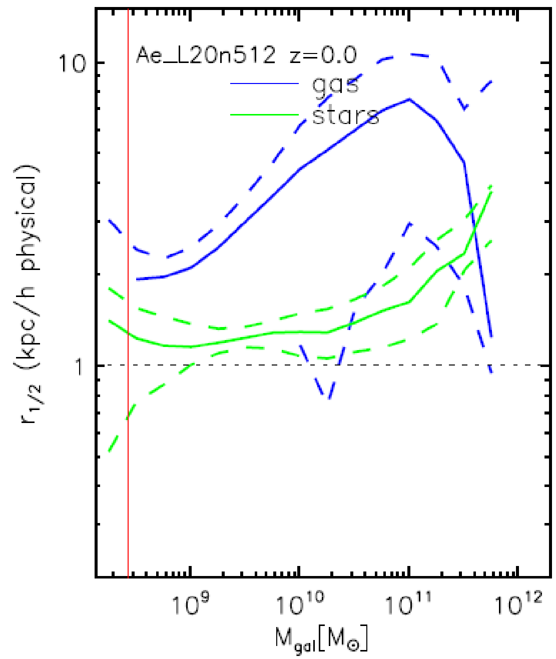


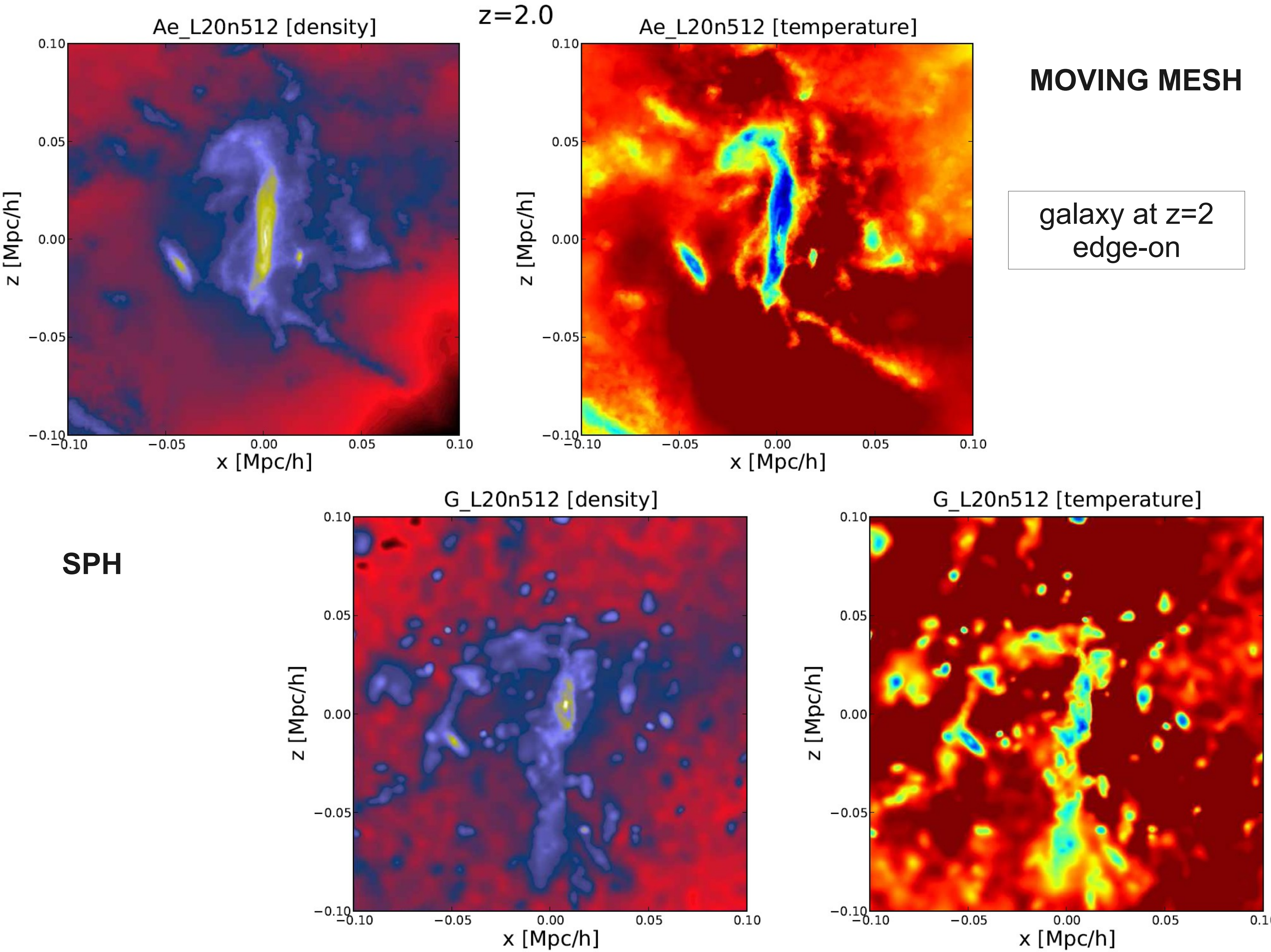
half mass radii
typically larger
with moving mesh

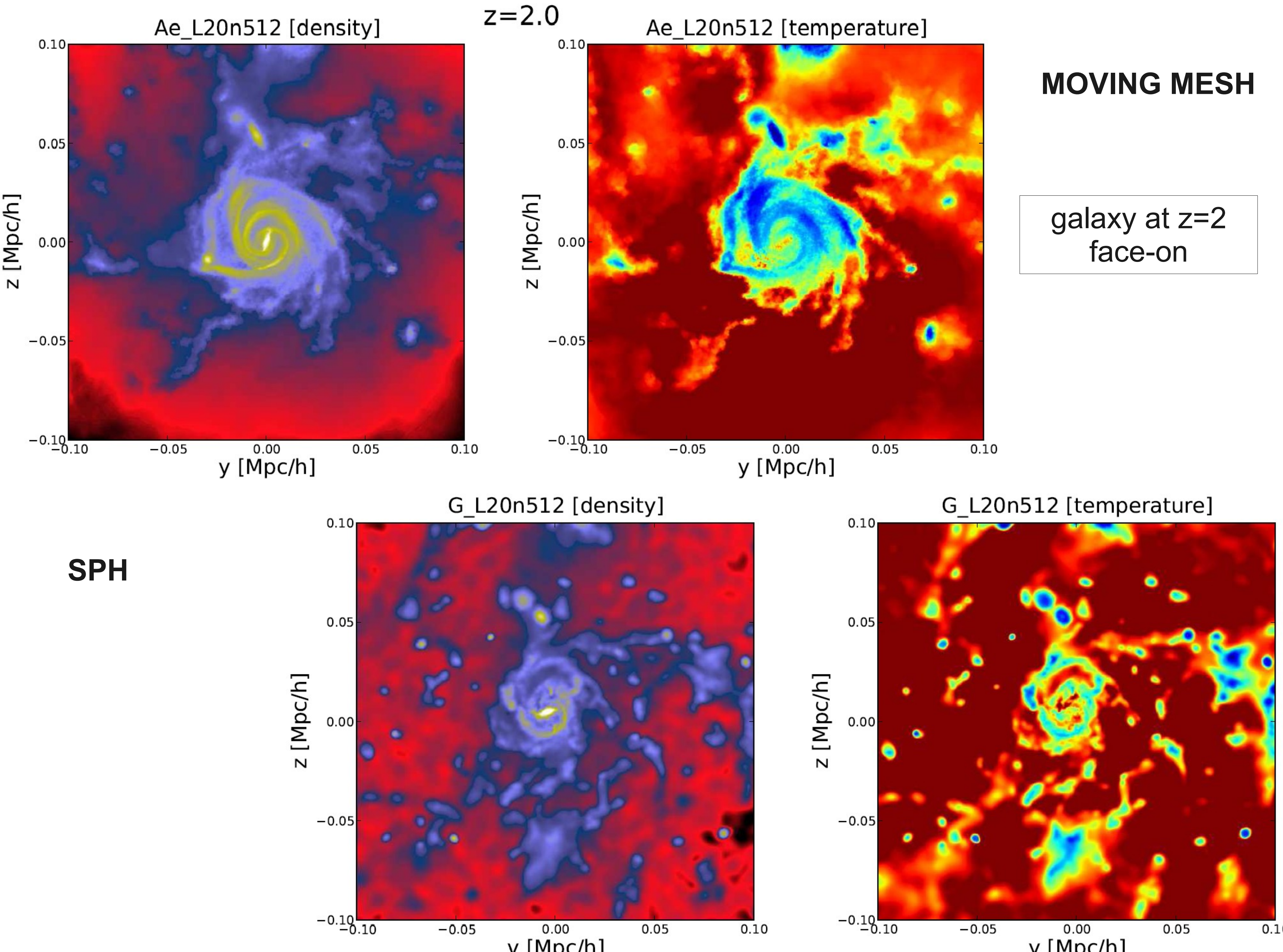


(specific angular momentum
typically larger
with moving mesh)

SPH




z=2.0
Ae_L20n512 [density]
Ae_L20n512 [temperature]
MOVING MESH
galaxy at z=2
edge-on
SPH
G_L20n512 [density]
G_L20n512 [temperature]
z [Mpc/h]
x [Mpc/h]
0.10
0.05
0.00
−0.05
−0.10



z=2.0
Ae_L20n512 [density]
Ae_L20n512 [temperature]
MOVING MESH
galaxy at z=2
face-on
G_L20n512 [density]
G_L20n512 [temperature]
SPH
z [Mpc/h]
y [Mpc/h]
0.10
0.05
0.00
−0.05
−0.10

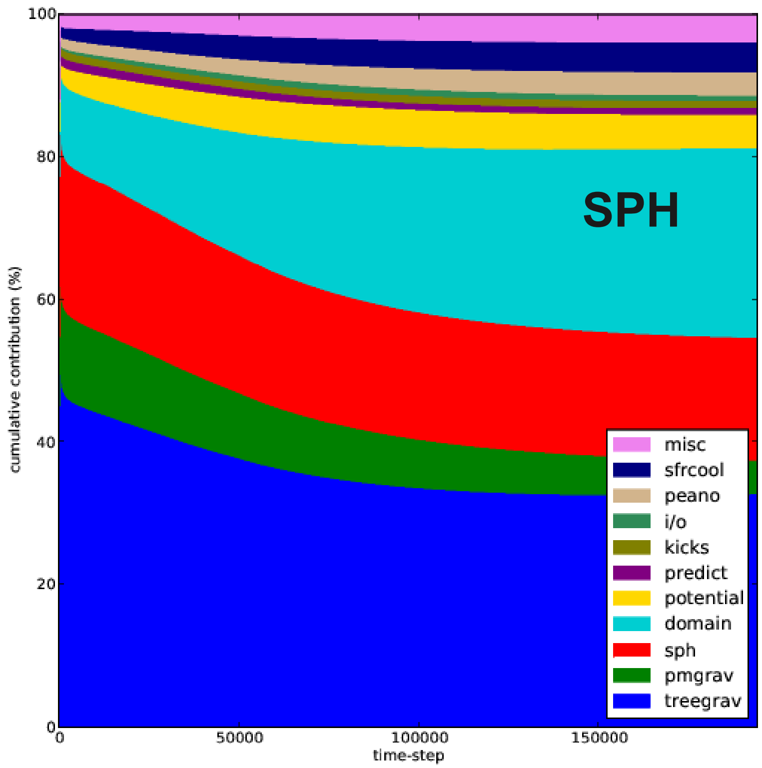
Performance

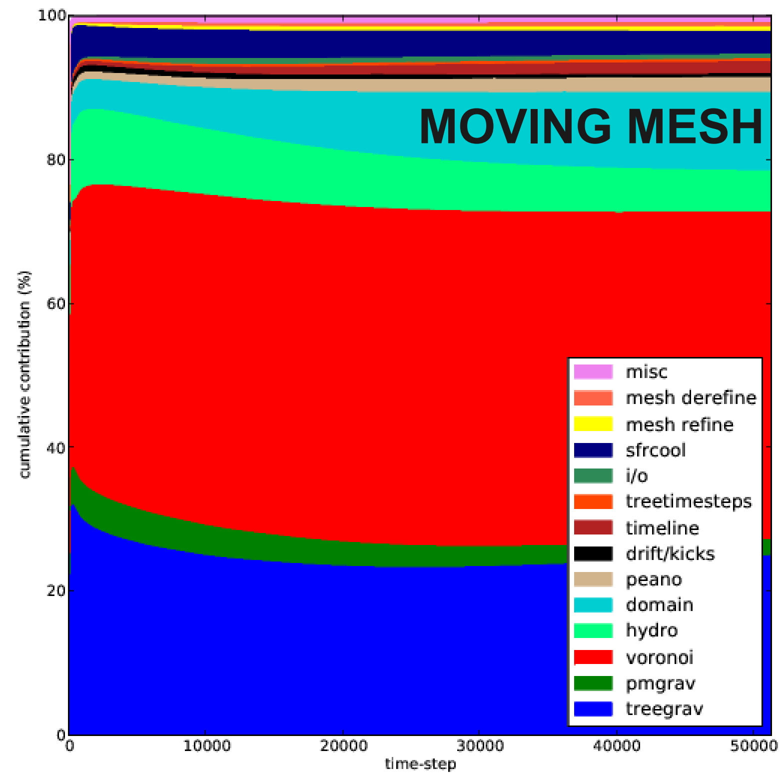
Total CPU time:

Gadget: $2x256^3 \rightarrow 64x190.000$sec

Arepo: $2x256^3 \rightarrow 64x240.000$sec

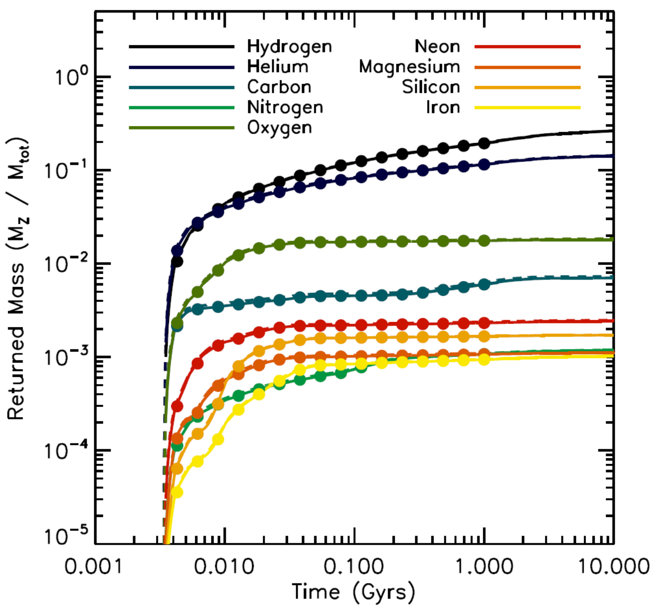
AREPO nearly as efficient as GADGET

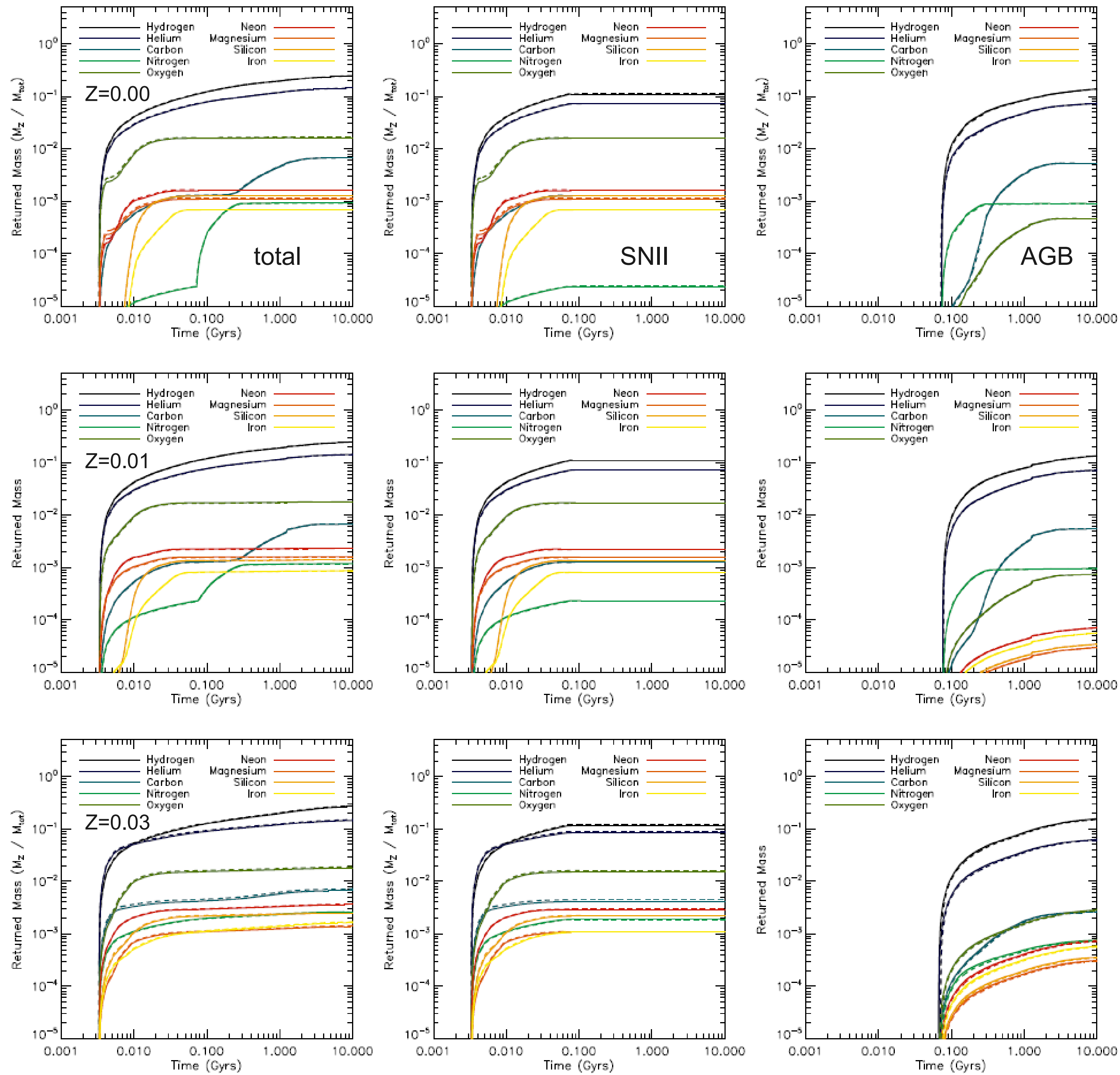




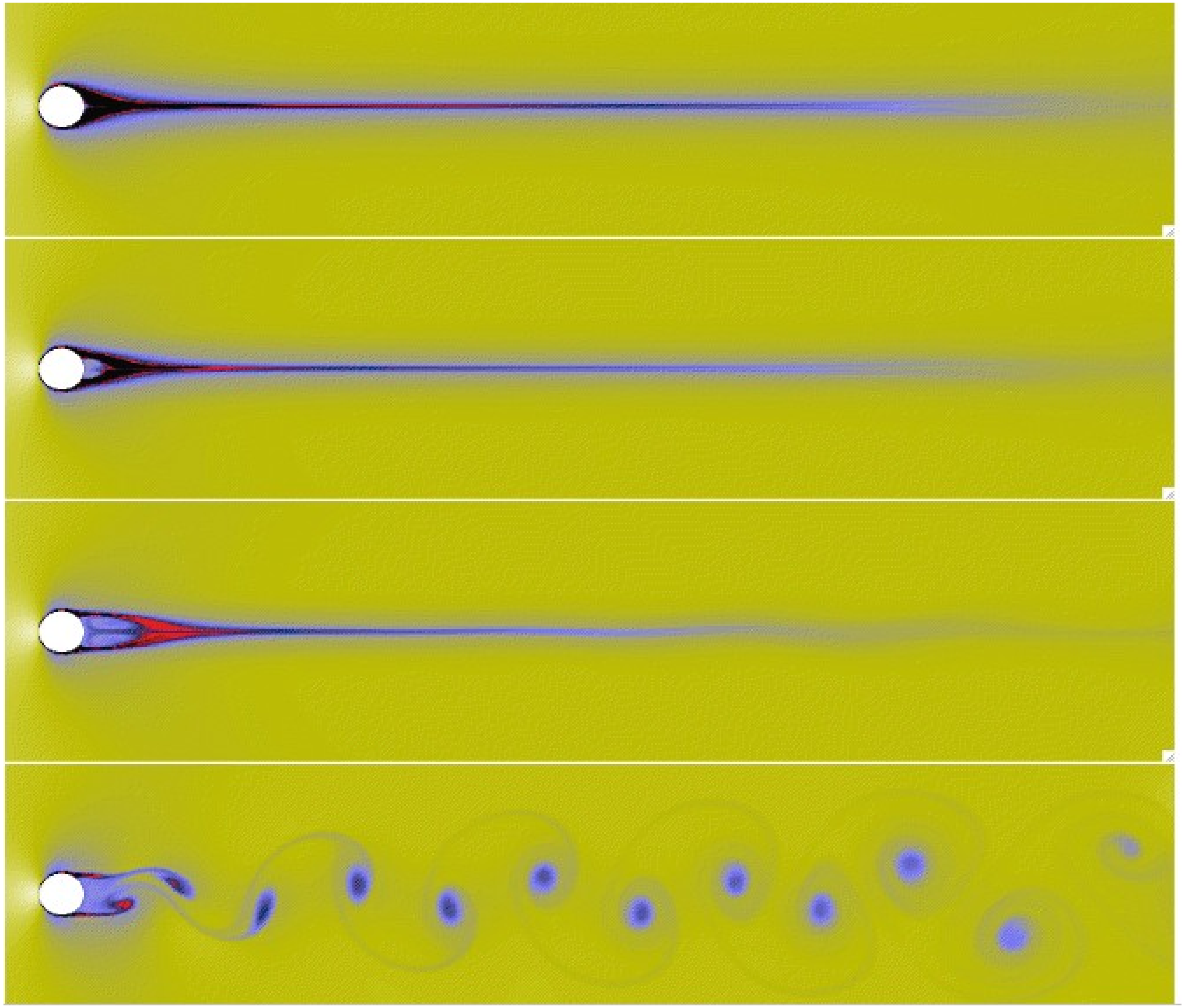
More Physics I: Chemistry

- chemical enrichment
- stellar mass loss
- metal line cooling





More Physics II: Navier-Stokes Terms



Re=10

Re=20

Re=40

Re=100

Munoz, Springel, Marcus, MV, Hernquist (submitted)

Implications

- hydro-solver matters a lot (not only the modeling of sub-resolution physics)

- tuning sub-resolution models based on a wrong hydro-scheme is questionable

- AREPO offers new hydro-scheme; might lead to new insights due to its flexible setup

- performance of moving mesh schemes (work and memory) is comparable to SPH codes